Supplementary Materials

ODD+

Model Description

This model was created in the agent-based modeling software NetLogo (v6.2.2),[1] and can be completely re-created using this standardized ODD+ document[2]. A randomized cityscape is created and populated with ‘dogs’ who live simulated lives that mimic important processes in free roaming dogs’ life histories. Agents acting as ‘dogcatchers’ attempt to collect dogs for intervention (using either vaccination, lethal removal, sterilization, or some combination).

Purpose

The model seeks to provide a highly flexible platform to test different methodologies of dog population management while ensuring the outcomes match real world scenarios as closely as possible. A previous model iteration by Yoak[3] as well as a similar model by Belsare and Vanak[4] form the basis for strong, biologically accurate foundation but have been enhanced here for ease of use and to handle more variable situations.

Entities, state variables, and scales,

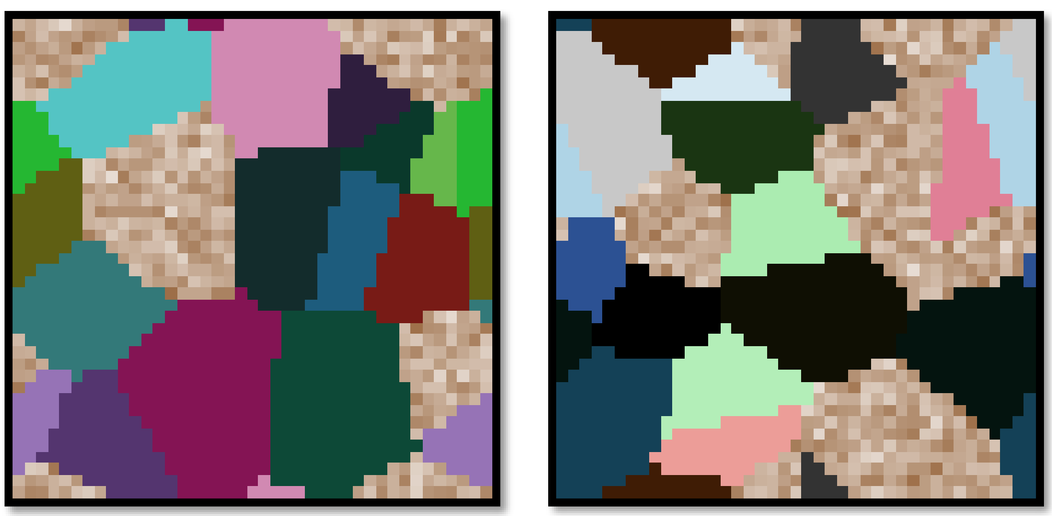
The model consists of two entities: dogs and dogcatchers and each has their own unique parameters (Supplementary Table 1). Dogs possess nearly all of the important state variables in the system such as location, sex, age, if they are reproductively intact, if they have been previously caught (i.e., tipped, as a common marking technique is to remove a small portion of one ear tip or create a recognizable ‘notch’ in the leading edge of one ear), and if they are currently protected immunologically by a vaccine.

Dogcatchers have a location and a limit to the number of dogs they can capture that month. Dogcatchers are also limited in how much ‘effort’ they can employ by limiting their distance travelled per month. Square patches of land represent approximately 1km x 1km space (however scale has little impact on the model and will vary as users produce their own city-maps) and are stochastically broken up into zones of variable size and dog carrying capacity during model initialization (Supplementary Figure 1). Each time step represents one month.

Entity	Parameter	Meaning	Default Value or Range	References
Dog Agent	Sex	Male or Female	-	-
	Age	In Months	-	-
	Sterilization Status	Sexually intact or not	-	-

	Vaccination Status	In the window of time where they have protection from a vaccine (either 12 or 36 months)	-	-
	Monthly Adult Mortality Rate	Probability of dying for dogs Under 1 year old	$1 - 0.75^{1/12}$	Derived from [5]
	Monthly Puppy Mortality Rate	Probability of dying for dogs Under 1 year old	$1 - 0.35^{1/12}$	Derived from [3,5]
	Litter Size	Average Number of puppies produced per reproduction	5.62	[6]
	Reproductive Rate	The probability that a dog will reproduce	See Supplementary Table 2 The monthly ratio of any reproductively intact female dog reproducing in that month.	Derived from [6]
Dogcatcher Agent	Location	The randomly decided XY coordinates	-	-
	Capture Limit	The maximum number of dogs that can be caught each moth	Varies by model from 100-300	-
	Distance Limit	The maximum distance that can be traveled to catch dogs each month	See Intervention Effort Limiting Submodel description	-

Supplementary Table 1. Agent and environmental parameters.



Supplementary Figure 1*. Two possible spatial distributions of generic city zones.*

Process overview and scheduling

Each month, a series of dog demographic and intervention submodels are applied to the whole population in a consistent fashion. First, dogs (female, sexually intact, sexually mature) can reproduce given certain constraints determined by the reproduction submodel. Next, all dogs grow older and have some age-dependent probability of mortality during the aging submodel. Then, any intervention actions that are taking place are handled by the dogcatcher actions submodels. Finally, a small number of young, intact dogs are generated by the abandonment submodel.

Design Concepts

Basic Principles

This system is heavily influenced by population dynamics in carrying capacity limited populations and focuses on the interplay of vacuums forming (through natural death or lethal removal by dogcatchers) and filling in (with compensatory reproduction). A model that accurately reflects the real world situation is highly beneficial to free roaming dog control [3,4,7,8].

Emergence

Our primary results, such as the total dog population or the vaccine coverage, emerge from the interplay between the intervention-focused submodels (sterilization, lethal removal, or vaccination) and the dog demographic submodels (reproduction, deaths, and abandonment).

Adaptation

Dog reproduction changes based on the surrounding local conditions. It is the normal rate at high local population densities but progressively at lower city densities. Dog mortality rates progressively increase as the carrying capacity is approached. The number of dogs that are caught by the dogcatchers is lowered by the effort-capping submodel because as the system contains fewer dogs (in both fertility and lethal control) or fewer dogs that were not previously caught (in fertility control) it becomes harder to find a new dog.

Objectives

Dogs have no in-built objectives other than to reproduce and survive, and no way to influence events. Dogcatchers nominally seek to reduce the dog population and/or increase the proportion of dogs who are vaccinated but, other than how many dogs were caught each month and what they do with a dog in hand, have no actionable decisions.

Interaction

Dogs express an limit on survival due to crowding. Dogcatchers ‘catch’ a dog and the relationship is determined by the model run’s management strategy (i.e., kill it, vaccinate it, sterilize it).

Stochasticity

All probability-based actions, including dog reproduction and mortality, where dogcatchers travel to, and initial seeding of the area are random effects.

Collectives

There are no collective agent groups, but patches are assigned to be part of a block of patches in a city zone during initialization. Each zone patch has the same dog carrying capacity as all other patches in the same zone.

Observation

Many demographics factors are collected each time step about dogs:

- Age
- Reproductive status
- Immunization status
- If they had previously been caught
- If they are catchable
- XY Location

And were collated into population-level indices:

- Number of dogs
- Number of vaccinated dogs
- Number of puppies

No information is hidden from observation and perfect knowledge of all indices is assumed for the system.

Initialization

The cityscape is created using the map randomization submodel to produce a novel city zone shape each model run but keeps the overall carrying capacity of the system the same. Then each patch creates a few dogs equal to 90% of its' individual per-patch carrying capacity and randomly assigns them demographic variables:

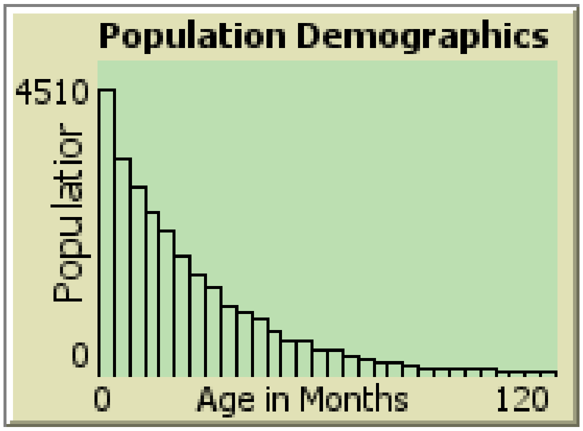
Reproductively Intact – Yes.

Vaccination Status – None.

Difficulty – In the standard model 5% are considered 'uncatchable' and cannot be targeted by intervention.

Sex – 50% probability to be assigned male at initialization (50% female)

Age – Assigned an age in months by randomly pulling a value from an exponential distribution of ages with a mean of 2 years (Supplementary Figure 2).



Supplementary Figure 2. *A sample model initialization of ages*

Every model run begins with 10 years of 'burn-in' time where the model runs without intervention to remove any effects of the initial model's characteristics.

Input Data

The model does not use input data to represent any known processes.

Submodels

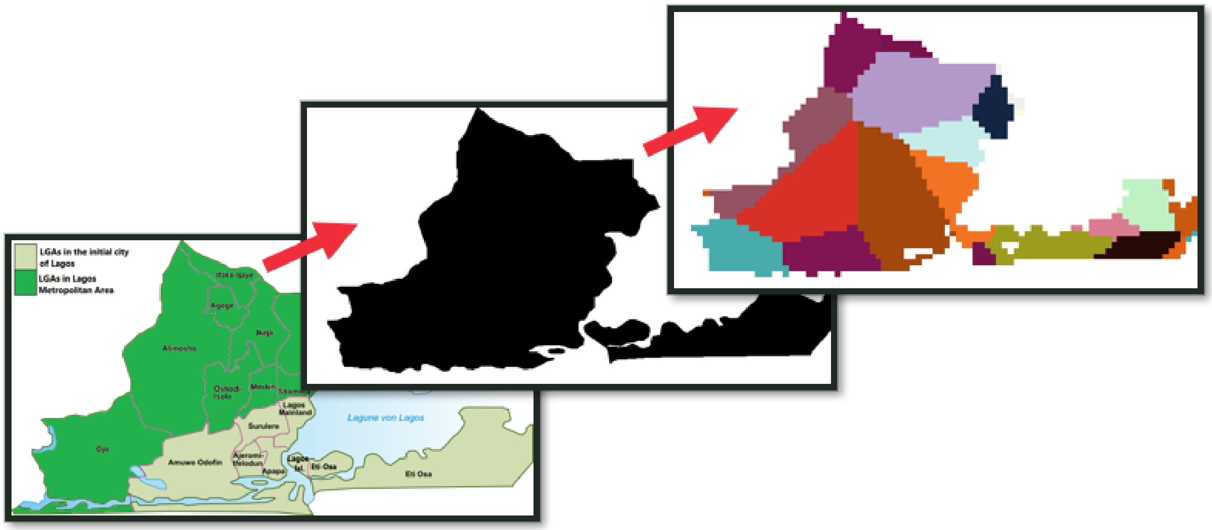
Generic *Map Randomization*

20 city zones are randomly generated by placing 20 placeholder agents at random XY coordinates. They then assign all the patches that are closest to them to be part of a zone which is assigned an equivalent dog carrying capacity. This per-patch carrying capacity figure is produced by pulling from a normal distribution with a mean equal to the target carrying capacity per km (30 in this model) and a standard deviation of 20% of the mean (30 * .2 = 6 here) to produce some degree of between-zone variation. 5 of these zones have their carrying capacity reduced to 0 to simulate areas out of the city or otherwise inaccessible to dogs.

When the 15 remaining zones are all assigned their carrying capacity, they are checked to ensure that the city as a whole still has a carrying capacity roughly equal to the target carrying capacity (30 dogs per patch here). If, say, one or more large zones had an exceptionally high (or low) randomly assigned carrying capacity then the city would be able to support an abnormally large (or small) dog population, and this would make between-run comparisons fraught. To avoid this, the final step of map randomization is to subtly lower a random zones per-patch carrying capacity by 1 and repeat this process until the city-wide average is only 10% above from the target city-wide average (this would increase a zone's carrying capacity in the event the city-wide average is more than 10% lower than the target).

Real Word Map Randomization

If the user chooses, they can insert a outline of a real world cityscape in black and have the model populate it with variable density zones and dogs identically to how a generic map is made (Supplementary Figure 3).



Supplementary Figure 3. *Taking a real-world location and producing a outline of the city, the model can populate that area with spontaneous zones.*

Dog Breeding

Female, intact dogs over the age of 12 months have a monthly probability to reproduce that follows the seasonality of Jaipur, India's street dog population (in the base model, but this can be adjusted easily with sliders). The number of female dogs who breed in a given year is set by the user (47.5% here) and then the model distributes these reproductive events throughout the year based on:

1. The lagging mean population of intact, adult female dogs
2. The monthly ratio of reproductions that take place in the current month (Supplementary Table 2)
3. The ratio of the current dog population vs the citywide carrying capacity.

If a female reproduces, she creates a litter with a size produced by rounding a normal distribution with a mean of 5.62 and a standard deviation of 1.0. Newborn puppies are randomly assigned male or female, born with no vaccination regardless of the mother's status, and disperse five patches away in a random direction. Some portion of dogs are assigned a status of 'uncatchable' at birth for their entire lifespan and this makes them wholly invisible to the dogcatchers.

Month	Probability of Reproduction
Jan	7.92
Feb	3.36
Mar	1.2
Apr	0.4
May	0.56

June	1.68
July	4.32
Aug	9.12
Sept	14.8
Oct	18.88
Nov	18.8
Dec	14.24

Supplementary Table 2 *The monthly ratio of any reproductively intact female dog reproducing in that month.*

If the population as a whole is pushed substantially below its' carrying capacity, the model simulates the compensatory reproduction effects by using the compensatory effects in Supplementary Table 3.

Current Dog Population : Carrying Capacity Ratio	Effect on Reproduction
>=0.9	0
<.9 and >=0.8	+2%
<.8 and >=0.7	+4%
<.7 and >=0.6	+6%
<.6 and >=0.5	+8%
<.5 and >=0.4	+10%
<.4 and >=0.3	+12%
<.3 and >=0.2	+14%
<.2 and >=0.1	+16%
<.1	+18%

Supplementary Table 3*. The compensatory reproduction rate increases on reproduction*

Dog Mortality

Each month, dogs have a probability to die determined by their age class, either older or younger than 1 year. Younger dogs have a monthly probability that corresponds with a yearly survival rate of 35% and older dogs' survival rate corresponds to a yearly rate of 75%. This matches approximately the observed mortality in the real world [5] and has been previously used in prior modeling efforts [3].

However, in this model, a dog's chances of survival decreases as the patch it is on approaches its unique carrying capacity. For example, Adults follow this formula in patches at <75% of carrying capacity:

$$Monthly\ Survival\ Rate = 1 - 0.35^{\left(\frac{1}{12}\right)}$$

And this formula in patches with >= 75% of their capacity filled:

$$Monthly\ Survival\ Rate = 1 - 0.35^{\left(\frac{1}{12}\right)} - ((0.35^{\left(\frac{1}{12}\right)}) * \frac{Count\ Other\ Dogs\ on\ Patch}{Patch\ Carrying\ Capacity})$$

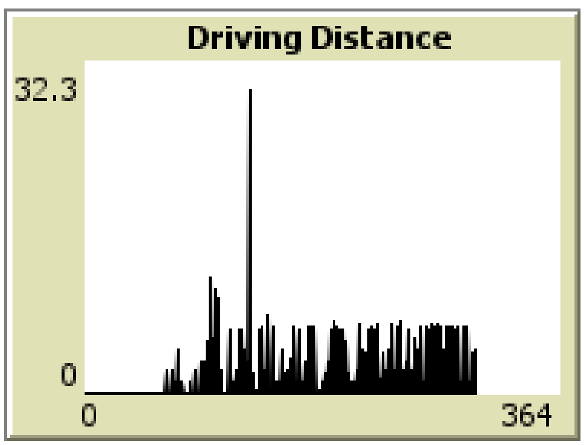
Abandonment

Each month, dogs are abandoned to the street by previous owners. To accommodate flexible model structures, this is assumed to be 10% of the starting stable population size at the end of the 'burn in' period and this 10% is spread out over 12 months. Newly abandoned dogs are assumed to be unvaccinated, randomly assigned either sex, have a 10% chance of being uncatchable, and aged from 0 to 12 months old.

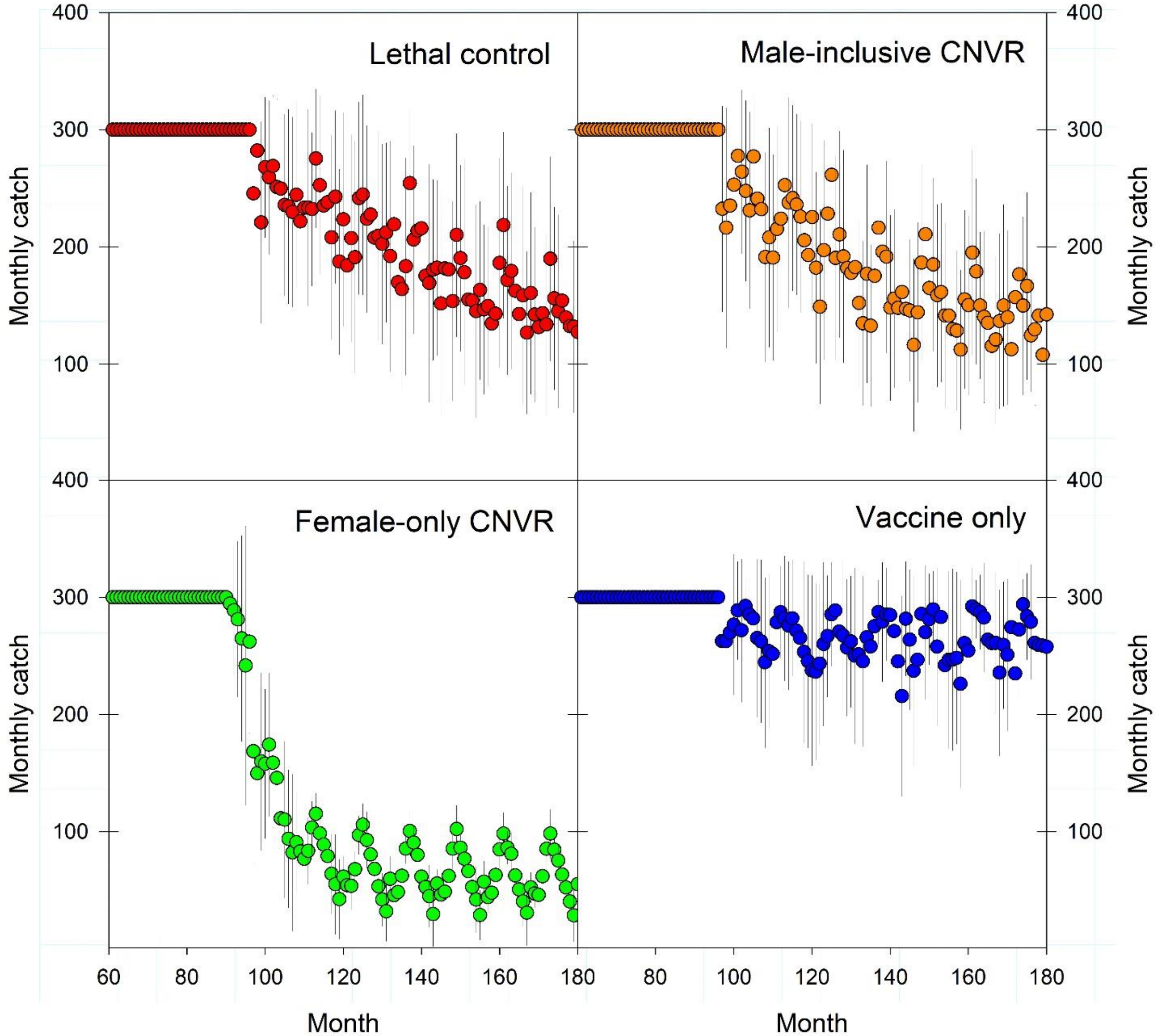
Intervention Effort Limiting

When the model begins intervention, it has a target number of dogs to capture each month and what intervention strategy will be applied to them. To account for the increase in effort that goes into finding new dogs in a city increasingly filled with already vaccinated and sterilized individuals (in the vaccine or fertility control-based strategies) or in a city increasingly depopulated (in the lethal or fertility control-based strategies), we begin to limit how far a dogcatcher can travel each day after a 3-year training period.

For the first 3 years of intervention a dogcatcher agent is created at a random location, then turns to the nearest catchable dog (one that is not part of the 'uncatchable' dogs, nor has been previously caught). It travels the distance to that dog then turns to face a new catchable dog. The sum of the distance required to travel to catch the target number of dogs is recorded for each month. The 10% highest distances are recorded, and the next highest distance is now the maximum allowable driving distance (Supplementary Figure 4). After this 'training period', the dogcatcher still moves towards dogs and records distance in the same way, but now when the maximum allowable driving distance is met, the month's intervention is finished irrespective of whether it met its target goal or not (Supplementary Figure 5).



Supplementary Figure 4. *A sample recording of the distances required to find the 300 target dogs in this model. Note the distances are capped after the initial 3-year training period.*



Supplementary Figure 5. The mean (and standard deviation) of dogs that were caught each month is continuous at 300 dogs per month for the first 3 years, then is reduced as the effort cap begins to be limiting.

Intervention Application

As a dogcatcher selects the closest catchable dog (over 6 months, not previously caught, sex-determined by management strategy), it alters the dog's status and increases the total number of interventions that were performed. This alteration can come in several forms, from killing the dog agent and removing it from the system (as in lethal control), or by sterilizing and/or vaccinating it (as in CNVR or vaccination strategies).

Pattern Oriented Model Parameterization

Models are not reality, but the approximation should behave as similar as possible under the narrow circumstances of the effect under investigation. We have made every attempt at generating a model with specific parameterizations that produce outputs with the same patterns as previously observed in the real world.

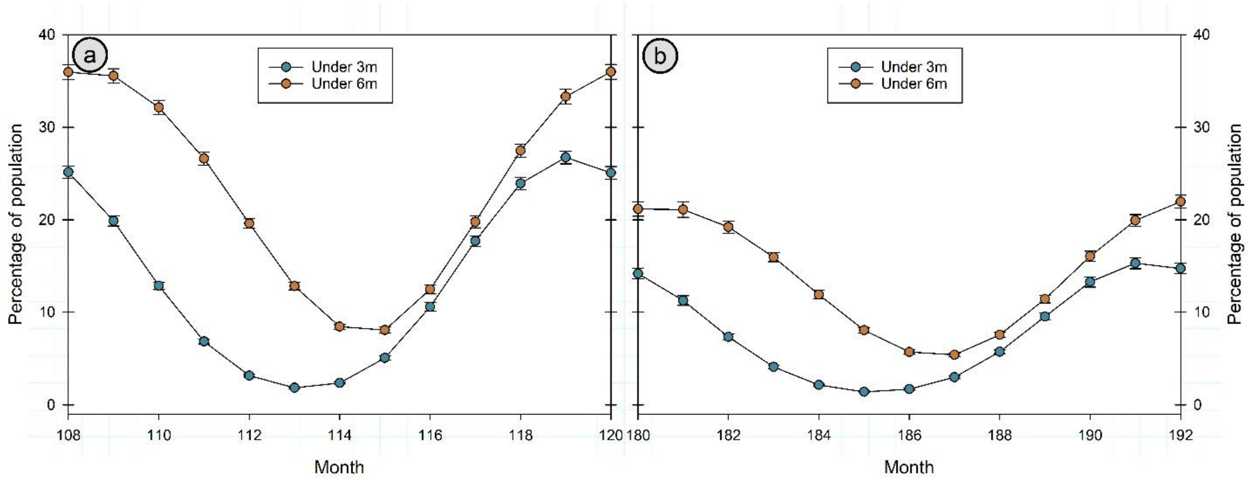
To test these effects in our model, we utilized a generic parameterization of:

- 15,000 carrying capacity
- 150 female dogs sterilized per month
- 75% adult survival
- 35% juvenile survival
- 10% abandonment
- 10% uncatchable

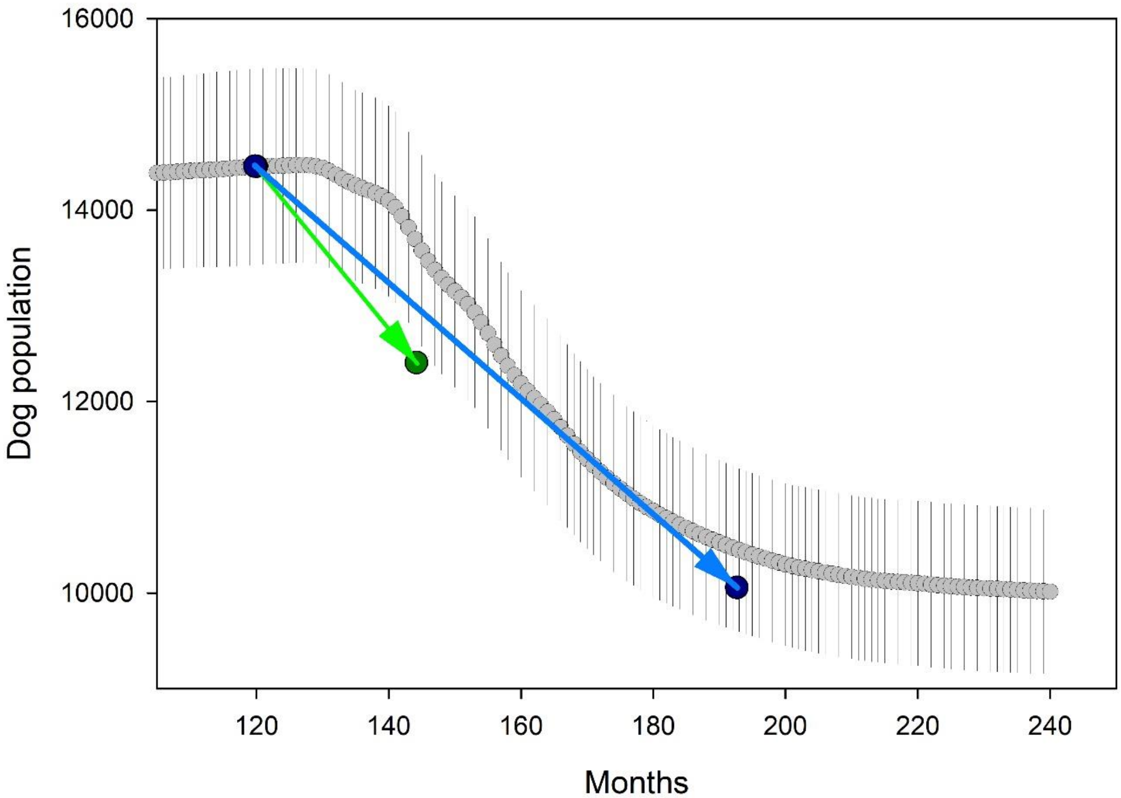
- Or referred back to the main paper's data.

Pattern	Source	Street Dog Sim	Quality of Pattern Match
Age	14.5% Juvenile Dog (<1yo) percentage without significant management [9]	~8-35% Juvenile dog (<6m) variation throughout the year prior to management (Supplementary Figure 6)	Moderate
	~27-4% Puppy (<12w) percentage varying throughout the year prior to intervention[10]	26-2% Puppy (<3m) variation throughout the year before intervention (Supplementary Figure 6)	Excellent
	~12-1% Puppy (<12w) percentage varying throughout the year after intervention[10]	15-2% puppy (<3m) variation throughout the year after intervention (Supplementary Figure 6)	Excellent
Population Change due to Female Only CNVR Intervention	15% Decline over 2 years[10]	~5% decline over 2 years (Supplementary Figure 7)	Moderate
	30% Decline over 6 years[11]	~27% decline over 6 years (Supplementary Figure 7)	Excellent
Intervention Related	60% of females in a population are neutered after 4y [11]	~54% of females are neutered after 4y (Supplementary Figure 8)	Excellent
	75% of population return to pre-lethal control intervention levels after 8m	Slower return to pre-lethal levels, generally 30-45m (main paper data)	Poor

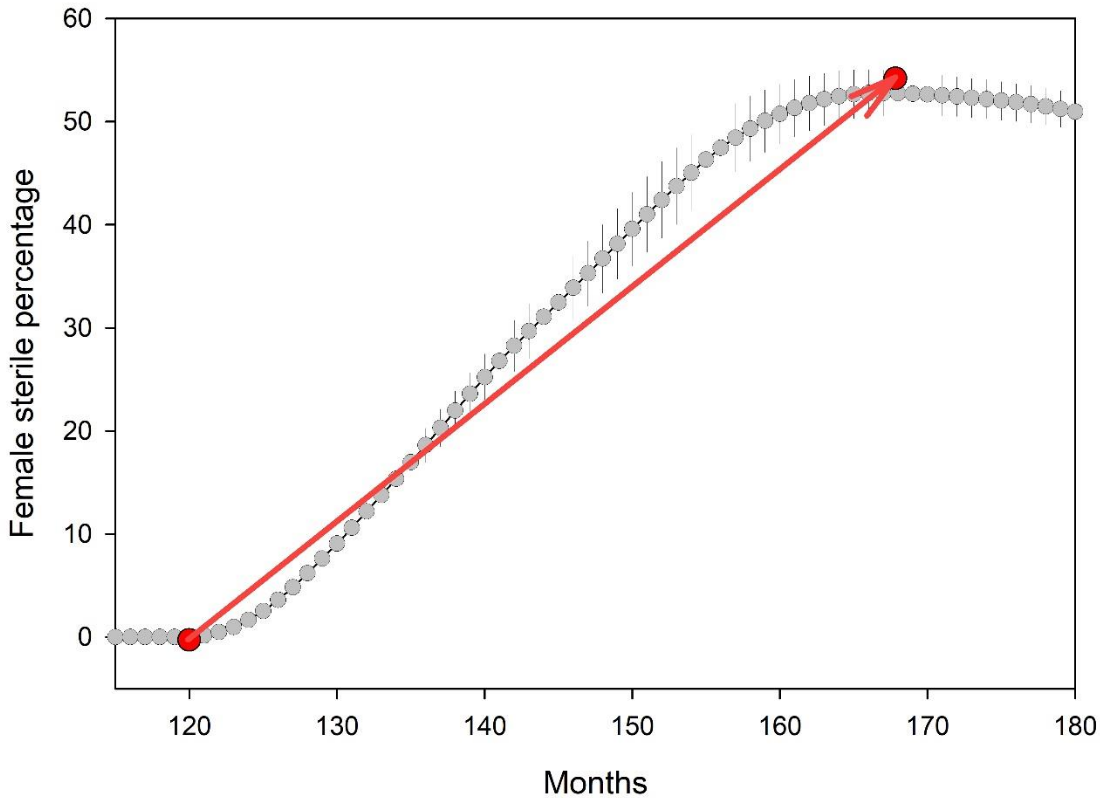
Supplementary Table 4. *Assessing the outcomes of the SDS model with real world demographics*



Supplementary Figure 6a. *The mean (and standard deviation) percentage of dogs that are under the age of 3 and 6 months in a generic parameterization of a pre-intervention population.* ***b.*** *The mean (and standard deviation) percentage of dogs that are under the age of 3 and 6 months in a generic parameterization of a post-intervention population. Here, intervention begins at month 120 and continues until 240.*



Supplementary Figure 7. *The decline in the mean (with standard deviation bars) dog population size over time for a generic parameterization of female only CNVR. The green arrow represent a 15% decline after 2 years of intervention. The blue arrow represents a 30% decline after 6 years of intervention.*

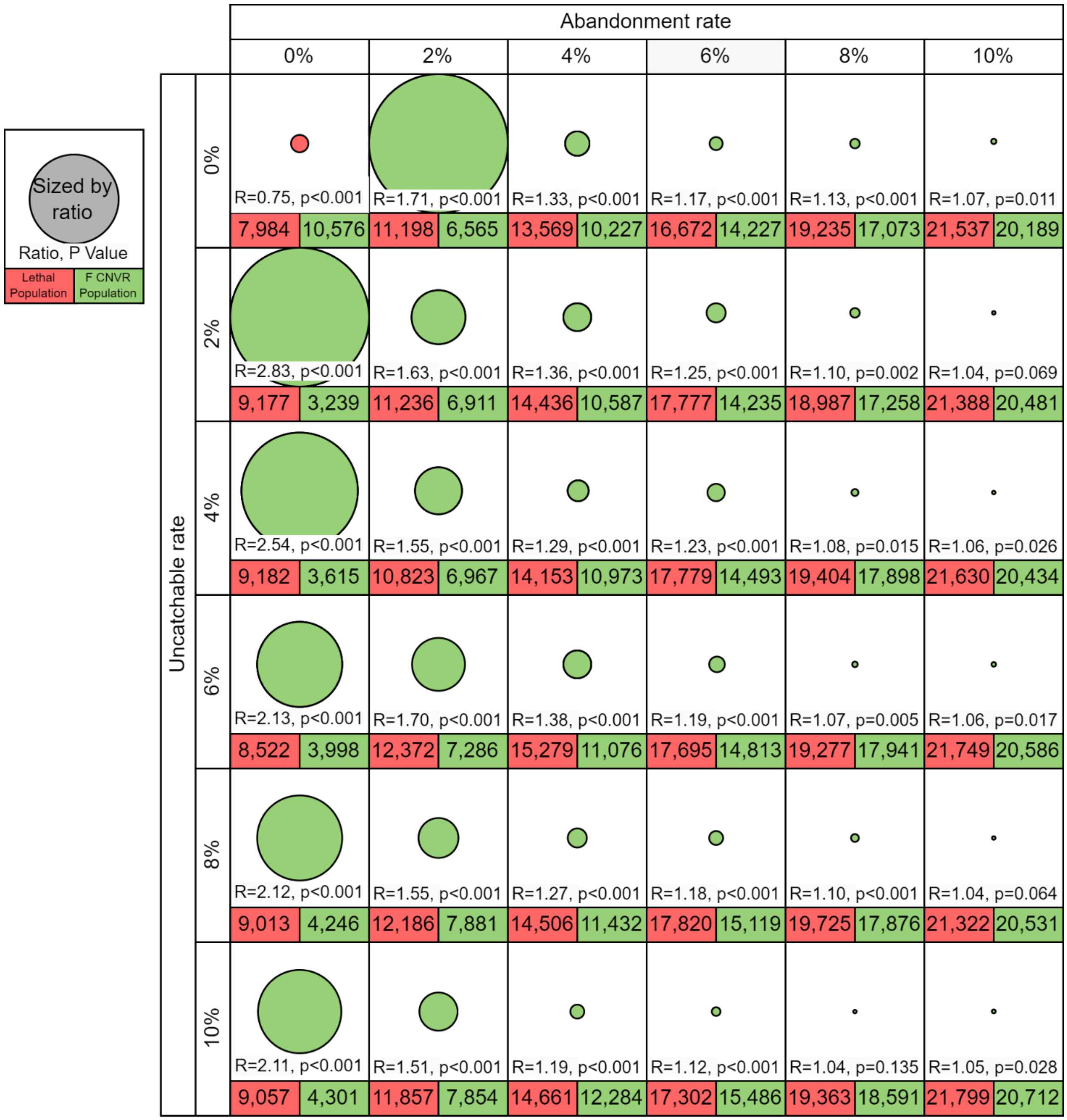


Supplementary Figure 8*. The rate of increase in the lagging yearly mean female sterilization percentage (with standard deviation bars) over time for a generic parameterization female only CNVR. The red arrow represents achieving 54% sterilized after 4 years.*

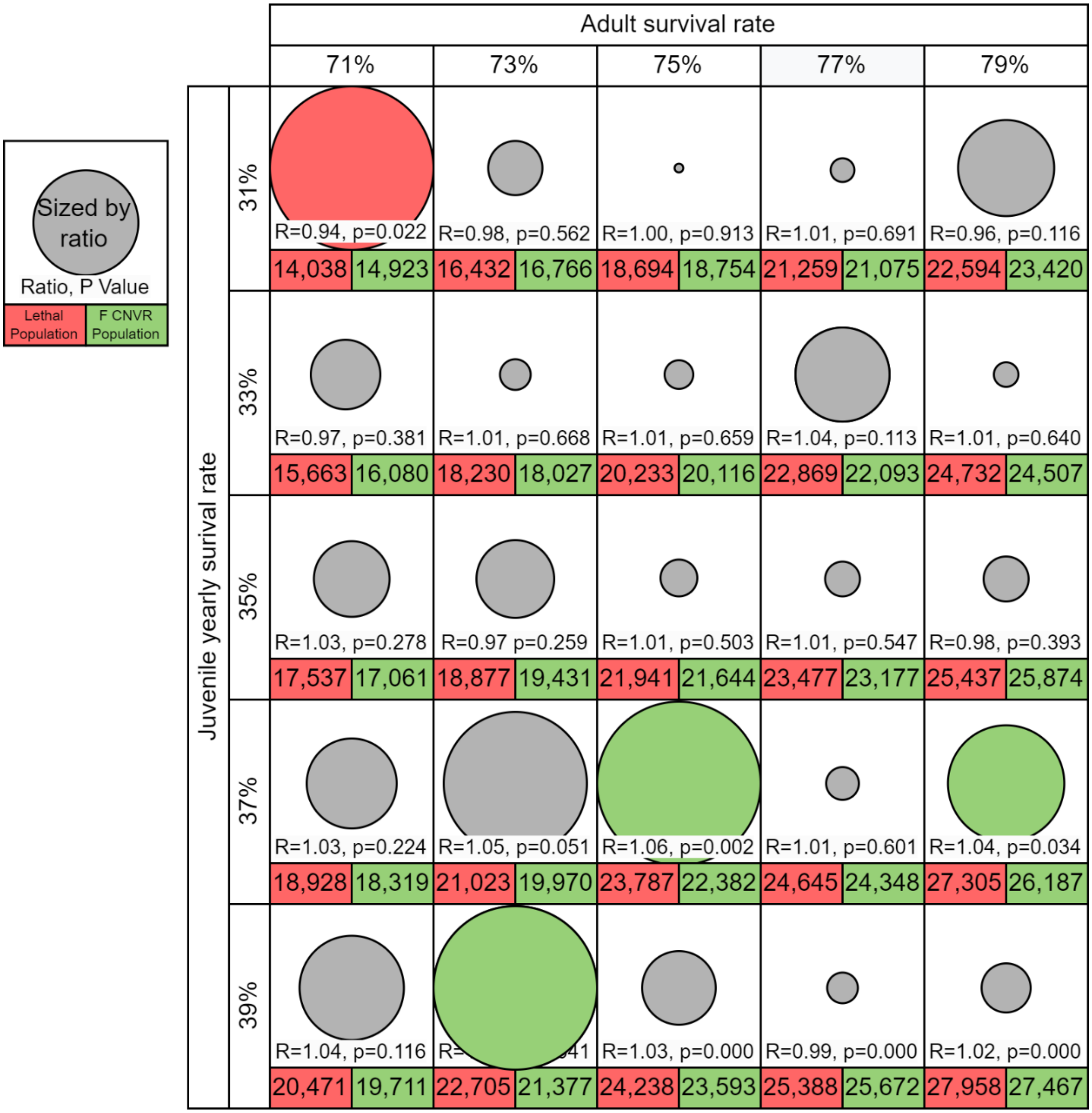
Sensitivity Analysis

Since this model's parameterization will invariably have an influence on the outcomes and not all local dog population's population dynamics match our 'standard' model here, we varied the important parameters that drive population dynamics (uncatchable percentage, abandonment rate, juvenile survival, adult survival, and reproductive rate) and investigated the final dog population achieved at the end of 10 years of intervention. This was done for both Lethal Control and Female-only CNVR after which a one-way ANOVA with Bonferroni correction was used to investigate if there were significant differences between scheme treatments.

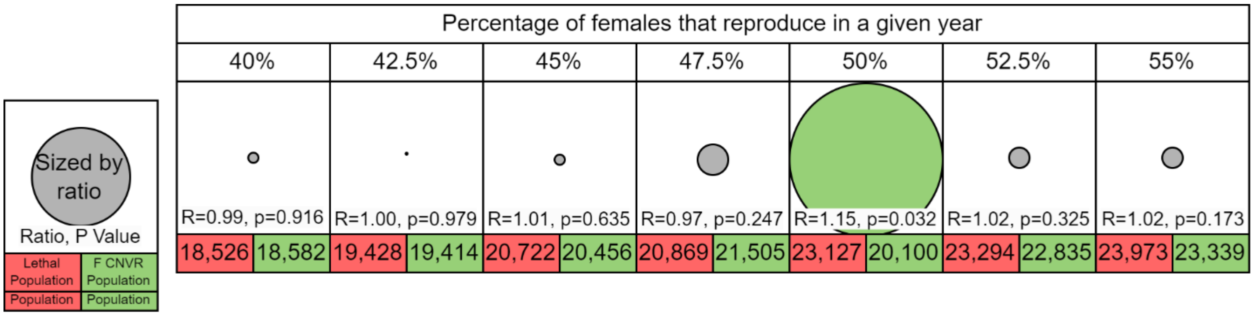
Uncatchable percentage and abandonment rate are both 10% in the standard model and we test variations from 0 to 10% here (Supplementary Figure 9). Survival was increased and decreased by 2% and 4% (Supplementary Figure 10). Reproductive rate was increased and decreased by 2.5%, 5%, and 7.5% (Supplementary Figure 11).



Supplementary Figure 9*. A comparison of the mean dog population size at the end of 10 years of intervention (preceded by 5 years of non-intervention burn in) with variable abandonment rates and uncatchable percentages. The mean population size is listed for Lethal Control / Fertility control and below is their ratio and one-way ANOVA significance. Comparisons are colored by what management strategy produces the lower population and shaded by the ratio (grey when non-significant).*



Supplementary Figure 10. *A comparison of the mean dog population size at the end of 10 years of intervention (preceded by 5 years of non-intervention burn in) with variable adult and juvenile survival rates. The mean population size is listed for Lethal Control / Fertility control and below is their ratio and one-way ANOVA significance. Comparisons are colored by what management strategy produces the lower population and shaded by the ratio. Grey color indicates no statistically significant differences.*



Supplementary Figure 11. *A comparison of the mean dog population size at the end of 10 years of intervention (preceded by 5 years of non-intervention burn in) with modified reproductive rates. The mean population size is listed for Lethal Control / Fertility control and below is their ratio and one-way ANOVA significance. Comparisons are colored by what management strategy produces the lower population and shaded by the ratio. Grey color indicates no statistically significant differences.*

Additional Sensitivity Investigations

Our 'standard' model structure assumes generally conservative estimates of the ability to vaccinate, including the following parameterizations:

- 10% of dogs are uncatchable.
- Dogs with an age of 6 months or older are caught for intervention (this is considered conservative because of the high mortality rate of dogs below 1 year of age, hence a potential to 'waste' a vaccine in terms of maximum vaccination coverage).

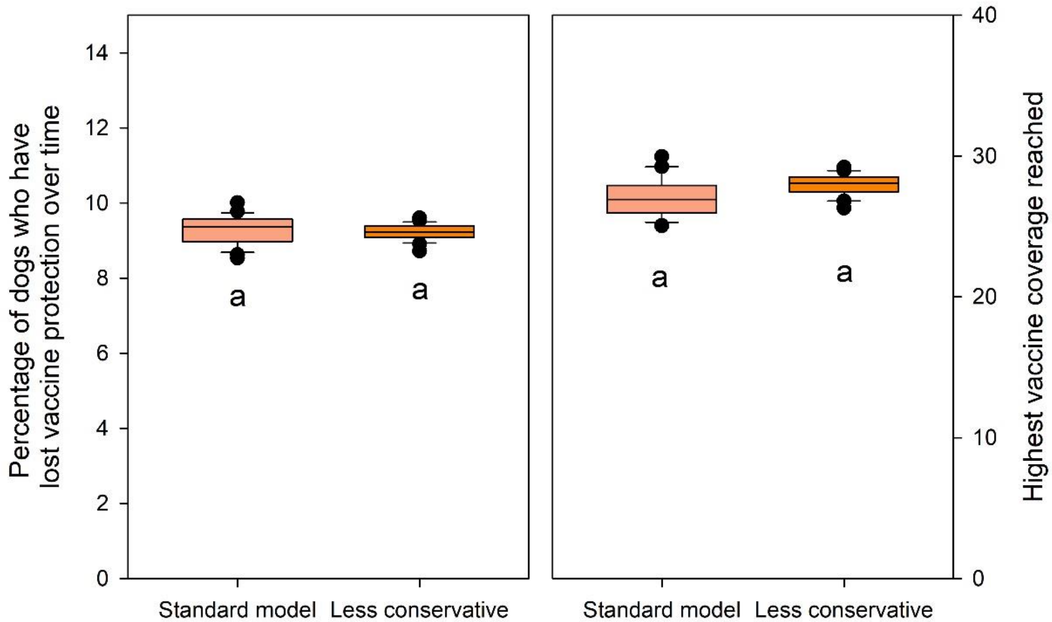
To test these assumptions, we constructed a 'less conservative' model parameterization with the following parameters:

- 2% of dogs are uncatchable.
- Dogs are only caught if they are over 12 months or older.

Both versions use the normal parameters of:

- Female-only CNVR scheme
- 35% Juvenile Survival
- 75% Adult Survival
- 10% Abandoned
- 30,000 Carrying Capacity

At the end of intervention, we compared the maximum vaccination coverage and the lapsed immunity percentage between these two model parameterizations using a one-way ANOVA (Supplementary Figure 12). We found that the standard model and less conservative model had no significant differences in the maximum vaccination coverage (mean = 27.10% vs 27.97%, p=0.372) or lapsed immunity percentage (mean = 12.91% vs 12.68%, p=0.464). These results show that the model is not significantly driven by these assumptions and should be robust to even larger changes in baseline parameters.



Supplementary Figure 12. *The differences between the standard model and less conservative assumptions model on the maximum vaccination coverage and the lapsed immunity percentage. The central line for each bar denotes the median, boxes denote the upper and lower quartiles, and whiskers display maximum and minimum excluding outlines which are denoted by filled circles.*

References

1. Wilensky, U. Netlogo. *http://ccl.northwestern.edu/netlogo/* (1999).

2. Grimm, V. *et al.* The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *Journal of Artificial Societies and Social Simulation* **23**, (2020).

3. Yoak, A. J., Reece, J. F., Gehrt, S. D. & Hamilton, I. M. Optimizing free-roaming dog control programs using agent-based models. *Ecological Modelling* **341**, 53–61 (2016).

4. Belsare, A. & Vanak, A. T. Modelling the challenges of managing free-ranging dog populations. *Scientific Reports* **10**, 1–12 (2020).
5. Reece, J. F., Chawla, S. K., Hiby, E. F. & Hiby, L. R. Fecundity and longevity of roaming dogs in Jaipur, India. *BMC Veterinary Research* **4**, 1–7 (2008).
6. Chawla, S. K. & Reece, J. F. Timing of oestrus and reproductive behaviour in Indian street dogs. *The Veterinary Record* **150**, 450 (2002).
7. Diaz, N. M. *et al.* Dog overpopulation and diagnosis of intestinal parasites on Santa Cruz Island, Galapagos 2016. *Preventive Veterinary Medicine* **157**, 99–104 (2018).
8. Shamsaddini, S. *et al.* Dynamic modeling of female neutering interventions for free-roaming dog population management in an urban setting of southeastern Iran. *Scientific Reports* **12**, 4781 (2022).
9. Nasiry, Z., Mazlan, M., Noordin, M. M. & Mohd Lila, M. A. Evaluation of Dynamics, Demography and Estimation of Free-Roaming Dog Population in Herat City, Afghanistan. *Animals* **13**, 1126 (2023).
10. Evans, M. *et al.* Free-roaming dog population dynamics in Ranchi, India. *Research in Veterinary Science* **143**, 115–123 (2022).
11. Reece, J. F. & Chawla, S. K. Control of rabies in Jaipur, India, by the sterilisation and vaccination of neighbourhood dogs. *Veterinary Record* **159**, 379–383 (2006).