Of Shared Homes and Pathways: Free-Ranging Dog Movement and Habitat Use in a Human-Wildlife Landscape in India

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Abstract

Background: Free-ranging dogs are widely considered to potentially have negative impacts on wildlife in shared landscapes. Understanding their use of these landscapes is therefore essential to develop effective management strategies in wildlife-adjacent regions. In this study, we investigated the movement patterns of free-ranging dogs in the protected area matrix of Mudumalai Tiger Reserve (MTR) in Southern India.

Methods: Fifteen dogs were collared from two adjacent villages with different levels of human habitation. We hypothesized that increased settlement cover would provide dogs with a greater human shield effect, allowing them more freedom of movement. We estimated dog activity ranges using autocorrelated kernel density estimates (AKDE) and characterized broad-scale movement through metrics including intensity of space use and mean distance from home. We then compared these metrics with respect to different variables to clarify underlying drivers of

movement patterns. Lastly, we analysed fine-scale habitat selection using integrated step selection analysis (iSSA).

Results: We found that free-ranging dogs in MTR have small activity ranges, with the mean AKDE activity range being 9.88 (median = 6.09 ha, SD = 7.69 ha, range 3.28-26.16 ha), and primarily utilise the area within 500m of their homes. No movement metric varied significantly with respect to any variable apart from intensity of use, which varied significantly between villages, indicating the dogs in the village with less human settlement restricted their movement more. iSSA revealed that dogs did not select for any specific habitat type other than human settlements and mostly moved within human settled or human-modified spaces, moving significantly faster in forest land than in any other habitat.

Conclusions: These findings support the human shield hypothesis and highlight the role of human land use in shaping the movement of domestic dogs, in turn mediating potential effects of dogs on wildlife. Our study shows that dogs show plasticity in space use even at fine scales of 5km or less, which has important implications for management strategies that aim to curb dog movement.

Key words: Domestic dog, telemetry, movement, human shield hypothesis, Mudumalai Tiger Reserve, step-selection analysis, human-wildlife interface

Introduction

As the most abundant carnivore on earth with a long history of domestication [1], dogs are as widely distributed as humans, with the most abundant category possibly being rural or village dogs [2]. These dogs are highly likely to be free-ranging, with previous studies on rural dog demography across the world indicating that a major proportion of village dogs are free to roam without any restraint, whether alone or in the company of humans [3–6]. In areas close to natural ecosystems, free-ranging dogs can have a range of negative impacts on wildlife [7,8], potentially ranging from mild to severe depending on the local socio-ecological context [9]. Broadly, the most common negative impact of dogs on threatened wildlife is predation, estimated at 78.9%, followed by disturbance (such as barking, chasing or harassment) and disease transmission at 7.0% and 4.5% respectively, and lastly competition with native carnivores (1.5%) and hybridisation with wild canids (1.0%) [10].

In order to clarify the true extent of these effects, understanding how dogs utilise wildlife-adjacent landscapes is perhaps the most necessary avenue of research, as patterns of movement and their driving factors underpin all subsequent impacts, from disease transmission to predation. A metric as fundamental as the home range (or activity range, for short-term studies) can vary regionally, seasonally, and individually, as previous studies from Australia [11–16] Chile [17], Kenya [18], Cambodia [19] and Mexico [20,21] have shown. It follows that roaming behaviour and habitat use, aspects of interest from a wildlife conservation perspective, may be as varied and may depend on a wide range of natural as well as anthropogenic factors. For example, dogs that disrupted sea turtle nests to scavenge for eggs were fed significantly less food by their owners compared to dogs that did not scavenge [21].

The need for research on dog-movement is particularly pressing in India, where the majority of the dog population is free ranging [22] and may often come into contact with increasingly fragmented natural ecosystems [23] that harbour a rich diversity of wildlife [24]. Previous studies have investigated other impacts of dogs on wildlife in India [25–27], with one study recording reports of negative interactions between dogs and 80 wild species [28]; however, to our knowledge, only two studies have estimated free-ranging dog movement ecology in rural or wildlife adjacent areas, both in the state of Maharashtra [29,30]. Of these, only Vanak and Gompper (2010), utilised telemetry to estimate home range and habitat use. As free-ranging dogs may exhibit spatial behaviour that is highly context-dependent, fine-scale telemetry offers a much-needed tool to document their movement ecology in matrix landscapes with joint human-wildlife presence.

In this study, we address this research gap utilising a fine-scale telemetry study on village dogs from a multiple-use landscape of a protected area in Southern India. As rural free-ranging dogs are usually closely associated with human habitation [1], we investigate how dog movement is affected by the relative presence of this habitation. We collared dogs in two different villages inside the forest with varying levels of human population, built up area, and village-forest boundary length. We hypothesize that a higher proportion of built up area, in conjunction with a smaller village-forest boundary, will produce a human shield effect [31] that allows dogs more freedom of movement in a landscape dominated by forests and wildlife. To test this hypothesis, we designed a study with two objectives: 1. Estimate and compare activity ranges and movement metrics between villages and 2. Evaluate how dog use of habitat types differs between villages.

Materials and Methods

Study area

The study was conducted in the villages of Masinagudi and Moyar, in Mudumalai Tiger Reserve (henceforth, MTR), Tamil Nadu, India. MTR is a protected area contiguous with multiple other wildlife sanctuaries, forming an integral part of the Nilgiri Biosphere Reserve in the highly biodiverse Western Ghats. Several villages are embedded within MTR, forming a matrix landscape where human settlements and major roads are interspersed within the forest. The study sites, Masinagudi and Moyar, are situated towards the centre of the Reserve on the Sigur Plateau, where the primary vegetation types are dry deciduous and dry thorn forest. MTR supports a variety of mammalian wildlife, including tiger (*Panthera tigris*), leopard (*Panthera pardus*), elephant (*Elephas maximus*), dhole (*Cuon alpinus*), chital (*Axis axis*), sambar (*Rusa unicolor*), blackbuck (*Antilope cervicapra*), black-naped hare (*Lepus nigricollis*), gaur (*Bos gaurus*), and sloth bear (*Melursus ursinus*) (32].

As the villages are situated within the forest, the village boundaries are routinely utilized by humans and domestic animals as well as wildlife (SVK, unpub. data). Masinagudi is a smaller village with a larger population of 1641 households (as of the 2011 Government of India census), has more contiguous built-up area, and hosts several facilities unavailable at other villages including garages, medical stores and clinics, multiple eateries, and a petrol pump. The major source of income for most residents is from tourism, by running homestays or driving safari jeeps. In contrast, Moyar hosts 486 households, with houses clustered in a few small settlements dispersed among fallow or agricultural land, which occupies the majority of the village area. Here, income is primarily derived either from agriculture or from working at the Electricity

Board, which has implemented a hydroelectric project at the Moyar dam. Masinagudi and Moyar are situated 6.8km apart by road, separated by a straight-line distance of 4.7km. The study area is shown in Figure 1.

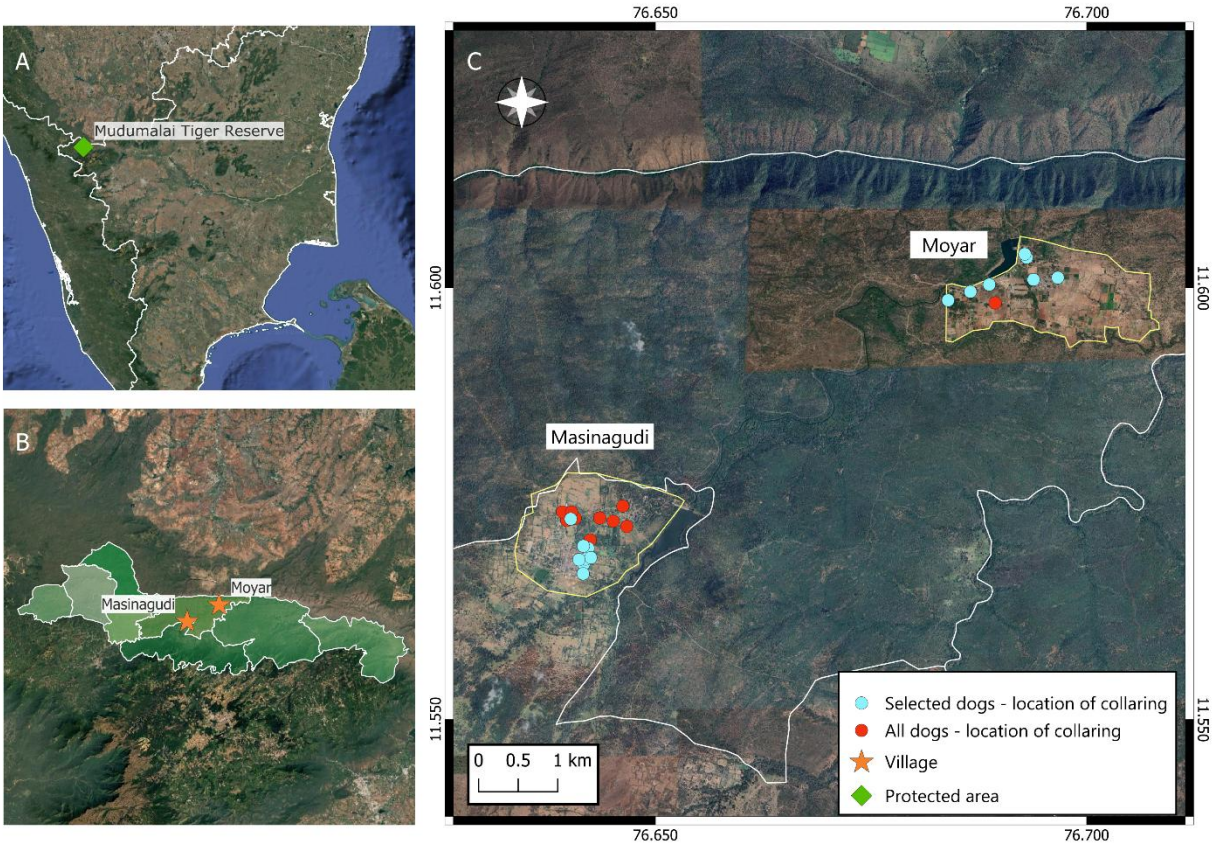

Figure 1: Map of the study area (C) with Masinagudi and Moyar village boundaries outlined in yellow. The red and blue dots show the location of collaring of all the dogs, with blue dots indicating those retained for analysis. The inset maps show the study area location in India (A) and in the state of Tamil Nadu (B).

Dogs are commonly kept by most people in this landscape, primarily as security against wildlife but also as pets (SVK, unpub. data). Dogs usually accompany owners and livestock [cattle, goats

and sheep) during grazing. Dog management has been ongoing since 1997 in the form of vaccination and sterilization programmes, carried out by local animal welfare organisations (India Project for Animals and Nature, IPAN, and Worldwide Veterinary Service-India, WVS-I). At present, almost 70% of dogs are sterilized and the male:female ratio is almost 1:1 (SVK, unpub. data).

Collar deployment

GSM GPS collars (by Arcturus Inc., Bengaluru, India) were deployed on the dogs with the permission and assistance of the owners. A total of 26 dogs were collared between September-November, 2024. The collars were set to record location every 5 minutes, with an accuracy (HDOP) of ten metres or less, and we aimed to place each collar for a maximum of ten days. In practice, the number of deployment days varied as owners sometimes requested that the collar be removed early or the collar was reported to have come off on its own, resulting in a range of deployment durations of 3-10 days. The dogs were all photographed and several demographic variables were recorded using the phone app Epicollect [33], including sex, sterilization status, approximate age according to the owner, and the GPS location of the owner's home. All dogs were adults and were fed a minimum of once and a maximum of thrice per day by the owner.

Analysis

The collated GPS data from all the collars comprised 27,850 GPS points after excluding points collected outside deployment times. Of the initial 26 collared dogs, the data from four dogs were

153 completely lost due to collar error or premature collar removal by unknown persons. The data
154 uploaded to Movebank is therefore from the 22 remaining dogs. Outliers were removed through
155 the online Movebank interface in two steps, first using a speed filter (excluding points that would
156 require the dog to move at a speed > 5 m/s) and second manually. Points removed manually were
157 presumably due to poor satellite reception and were implausible for accessibility (e.g., the middle
158 of a fenced waterbody) or distance reasons (e.g., random single points > 500m away from
159 clustered preceding and subsequent points). 4193 points were removed with the filter and 186
160 were removed manually, resulting in a final count of 23,471 points. Subsequent data analysis
161 was conducted with the data downloaded from Movebank (see Data Availability) in order to
162 ensure conformity to a standard format. Of the 21 dogs included in this dataset, seven were
163 excluded during analysis as their data were excessively patchy and the number of data points
164 collected for each of the six was less than 300, which is approximately only one day of data [one
165 full day of data would comprise 288 points, as 12 points were collected every hour for 24 hours).
166 Three additional points were removed due to low accuracy (HDOP > 10). The final dataset
167 therefore comprised data from 15 dogs with robust datasets.
168
169 *Movement Metrics:*
170
171 To understand if the movement of the dogs differed between villages, we utilised multiple
172 different movement metrics. We calculated the activity range, or the area traversed by the dog
173 during the short-term period of deployment [19]. To do so, we utilised the package *ctmm* (v1.2.0)
174 [34] in R version 4.4.1 [35] to estimate the activity range for each dog using autocorrelated
175 kernel density estimation [AKDE], similar to Wilson-Aggarwal et. al, 2021. Six models were

fitted to each dog's spatial data, and the best fit model was selected using the *ctmm.select* function. The models included Ornstein-Uhlenbeck (OU), OUF (Ornstein-Uhlenbeck with foraging), and IID (Independent and Identically Distributed), which does not consider autocorrelation. After model selection, the 95% AKDE activity range was calculated. We also calculated two movement metrics; first, the intensity of use, or the active time spent per unit area, defined as the ratio of the total distance moved during the sampling period to the square root of the 100% minimum convex polygon (the maximum area used by the animal) [37,38] using the package *amt* [39]. Second, the mean distance between the owner's home and each GPS fix for each dog. The distance between home and the dog's location was calculated using the package *sf* [40] for every set of GPS coordinates recorded, and subsequently averaged to provide the mean as a measure of how far away from home each dog tended to travel during the study period. We repeated this process with the distance from the centroid of the activity range to assess whether there was any significant difference between the two.

The movement data were further categorised with respect to day and night for the mean distance from home, and with respect to sex of the dog and the village where the dog was collared, for both movement metrics as well as the activity range. Since these dogs were owned and fed regularly, the level of human subsidy was not included as a variable in this study. As the collaring period was relatively short, the difference between sunset and sunset times during the study was negligible; therefore, we used 0600-1800 hours as day time and 1800-0600 hours as night. We tested the difference between the movement metrics and activity range with respect to these variables with the non-parametric Wilcoxon rank sum test.

Habitat Selection:

We also evaluated the selection and movement of the dogs for different habitats. We classified the areas of each village into settlement, agriculture, fallow or scrubland [uncultivated land beyond settlements but within village boundaries), and forest land to understand habitat-wise dog movement (Fig. 2). Forest land included both deciduous forest and thorn forest vegetation types. We used land use/land cover Sentinel-2 imagery at a resolution of 10 metres, classifying specific land use types (such as fallow land) manually, given the fine scale of the study area. As an initial coarse assay of habitat selection, we used landscape imagery of approximately 70 sq. km, enough to maintain a buffer of 1 km in all directions from both villages, and calculated the proportion of dog presence with respect to habitat availability of each class type.

We then utilized integrated step-selection analysis, or iSSA [41] to study the fine-scale influence of habitat covariates on the habitat selection and movement rate of the dogs. iSSAs contrast the environmental attributes of each animal location with a set of random locations generated from the distribution of movement parameters (step lengths and turn angles) of the steps the dogs took [41]. As with other habitat selection analyses, iSSAs compare covariate values at used (animal GPS locations) and random points (locations generated using the distribution of movement parameter) for each animal step. iSSAs are considered to be an improved approach to habitat select analysis as the framework can simultaneously estimate coefficients of habitat selection and movement rate, potentially increasing the accuracy of both [41,42]. We generated 20 available steps per used steps from the observed movement parameter distribution of the dogs. As the data was collected at a very high resolution, we resampled the movement data to 15 minutes and 30

minutes to control and test iSSA models for spatial correlation. The village of origin of the dogs was considered as a random effect for habitat and movement to elucidate differences in movement between the two villages. We utilized the Poisson trick [42] and the variability in movement across villages using the random effect approach [43]. Models were fitted using the package "glmmTMB" [44] and visualized using package ggplot2 [45]. All codes to reproduce the analysis are publicly available [see Data Availability).

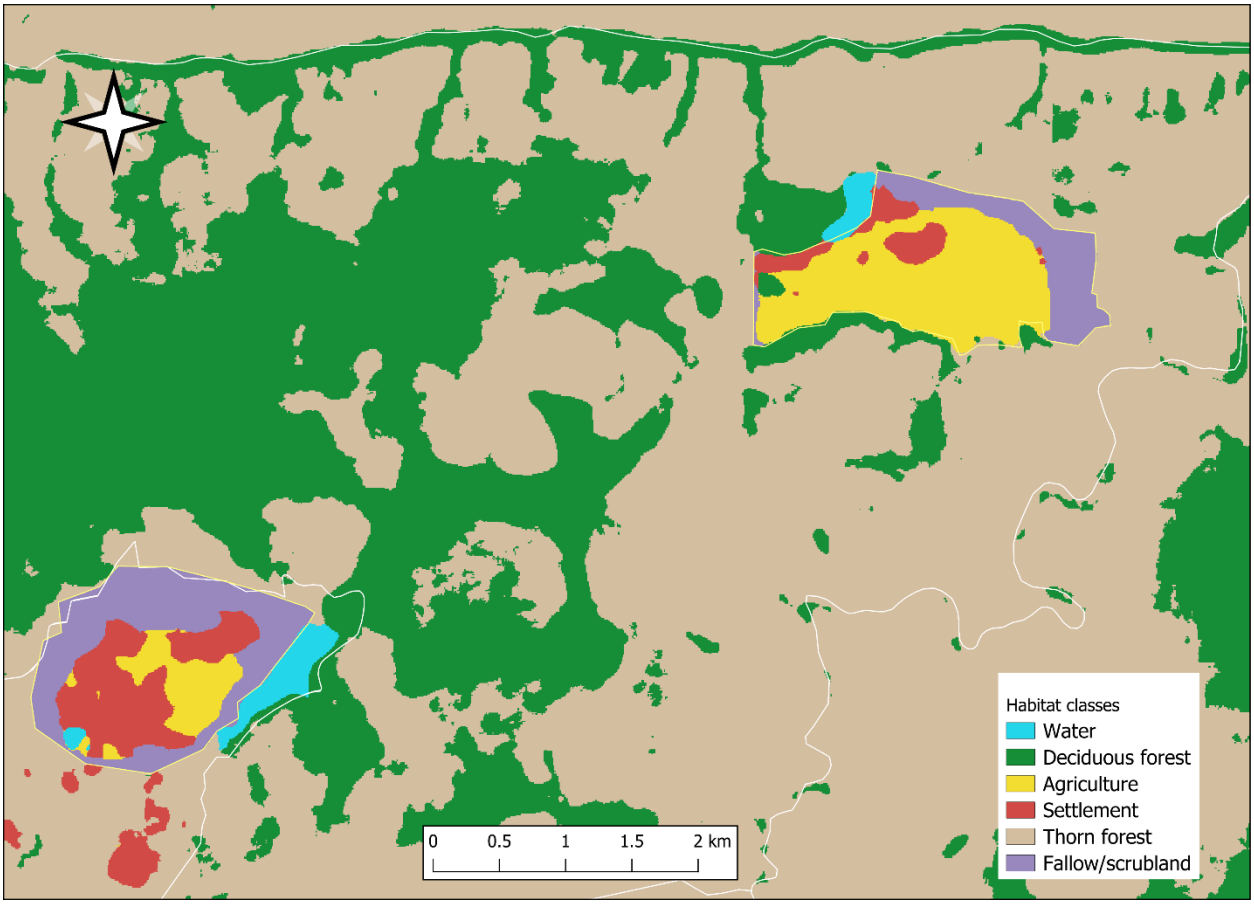

Figure 2. Map of the study area with classified habitats.

Results

Of the 15 dogs from 15 households, 8 were female and 7 male, with 8 from Masinagudi and 7 from Moyar, of which one male was unsterilized (see Supplementary Table S1). The average age of the dogs tracked was 5 (minimum 3, maximum 8). The mean number of tracking days was 8.07 (median = 9, range = 3-10). The total number of GPS fixes recorded and used for analysis was 22277, with an average points per dog of 1485 (range 619-2783). Post outlier filtering, the precision of the data was high (mean HDOP = 1.66, median = 1.47, range = 0 - 9.13).

The best fit model for all individuals was OU anisotropic, often with a ΔAIC of approximately 2 with the next best model, which was OUF anisotropic (see Supplementary Table S3 for all ΔAIC values), while IID was ranked last for all individuals. AKDE activity range estimates based on this model varied across dogs. The lowest activity range was 3.28 ha and the highest was 26.16 ha, estimated for a dog that routinely accompanied her owner during livestock grazing. The mean activity range was 9.88 ± 7.69 ha (median = 6.09 ha). For distance travelled from home, the longest distance for each dog ranged from 341.9 m to 1197.1 m, the mean distance from home across all dogs was 74.44 ± 119.53 m, and the median was 36.12m. 91.8% of all GPS points were within 250m of the home, while 98.4% were within 500m. Lastly, the mean intensity of use was 115.94 ± 54.50, and the median was 91.45.

We found no significant difference between mean distance from home and mean distance from the centroid, with the distance between home and centroid sometimes varying by as little as 10 metres; therefore, all further analysis was conducted with respect to distance from home only. When the three metrics, activity range, mean distance travelled from home for each dog, and the intensity of use for each dog, were compared with a Wilcoxon rank sum test with respect to day

and night (for mean distance from home only), sex, and village, the only significant difference (p value = 0.014) was between intensity of use in each village. The movement metrics for each dog are presented in Table 1, and the p-values and U statistic for each comparison are presented in Table 2. The intensity of use and activity ranges compared between villages are provided as a box plot (Fig. 3).

Table 1: Individual dog movement metrics.

Dog ID number	Activity range [ha)	Activity range 5%-95% CI	Mean distance from home [m)	Intensity of use
D1V1	11.459	10.318 -12.660	76.835	87.835
D2V2	4.485	4.240 - 4.736	58.948	213.082
D3V2	4.189	3.868 - 4.522	50.858	166.233
D4V2	23.860	21.323 - 26.535	124.933	179.025
D5V2	3.389	3.220 - 3.565	41.505	146.008
D6V1	26.163	22.971 - 30.670	127.269	72.462
D7V2	3.277	3.056 - 3.550	308.419	64.976
D8V1	4.564	4.369 - 4.828	45.343	137.936
D9V1	9.876	7.842 - 12.188	52.689	54.607
D10V2	19.606	16.214 - 23.316	99.701	91.446

D11V1	3.807	3.576 - 4.046	39.944	131.479
D12V1	7.189	6.456 - 7.961	54.108	87.589
D13V1	14.398	10.318 - 19.147	79.283	62.863
D14V1	5.797	4.811 - 6.875	49.048	48.887
D15V2	6.087	5.785 - 6.397	55.570	194.622

Includes 95% activity range, mean distance from dog home and intensity of use for all dogs included in the analysis. ID codes refer to the dog's serial number [D1) and village of origin [V1 or V2 for Masinagudi or Moyar respectively). Further details about dog demographic parameters, data collected and duration of collaring may be found in Supplementary Table S1.

Table 2: Wilcoxon test results for movement metric comparisons, with respect to different variables.

Metric	Variable	P-value	U statistic
Mean distance to home vs mean distance to centroid	NA	0.486	130
Mean distance to home	Day/night	0.148	148
Mean distance to home	Sex	0.867	30
Mean distance to home	Village	0.397	20

Activity range	Sex	0.336	37
Activity range	Village	0.336	37
Intensity of use	Sex	0.121	42
Intensity of use	Village	0.014*	7

Significant values (<0.05) are marked with an asterisk.

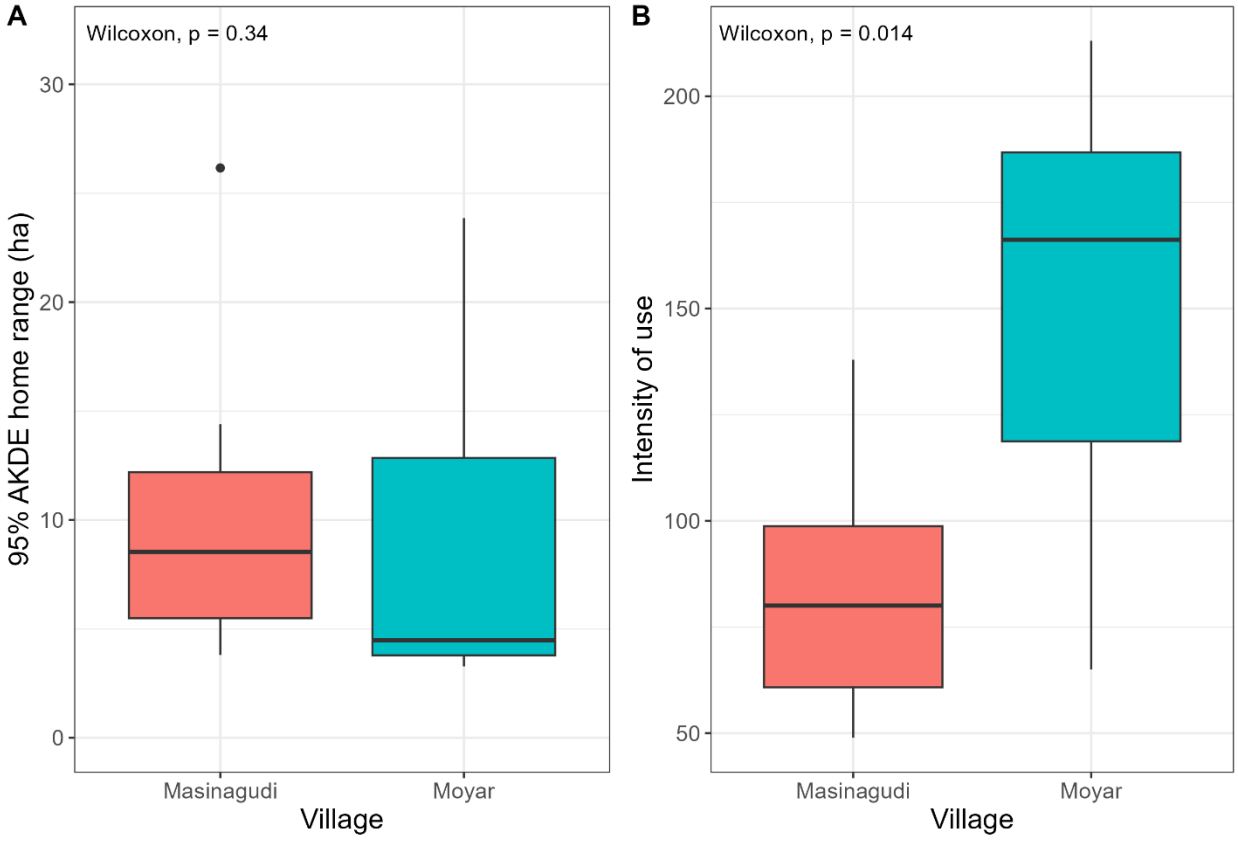

Figure 3: Histogram showing the differences in the home-range (A) and intensity of area use (B) for collared dogs from two villages. The values on the top left show the p-value from the Wilcoxon rank-sum test.

The initial coarse assay of habitat selection found that 85.9% of all dog locations (n=19145) were located in settlements, followed by 7.8% of locations (n= 1742) in agricultural areas and 2.6% (n=571) in scrub/fallow land. Together, 96.5% of all locations were in human-settled or human-modified habitats. With 1.96% of locations (n=436) in deciduous forest and 1.23% (n=273) in thorn forest, only 3.05% of locations were in the protected area. As the availability of settlements in the 70 sq. km landscape was 1.85%, while agriculture was 2.76% and fallow land was 2.56%, compared to 32.4% of deciduous forest and 59.89% of thorn forest, dogs strongly selected for human modified habitats.

This supported the results of the integrated step-selection analysis, which evaluated the fine-scale habitat selection of dogs from the study area. The outcome of iSSA was similar for both time scales (15 min, 30 min), with a higher standard error for the data resampled at 30 minutes (Fig. 4.); therefore, we used the results of the 15 min resampled data for further analysis. Of all available habitat classes, anthropogenic habitats (that is, settlements and agricultural land) were significantly preferred, while others were not. However, the habitat-movement parameter interaction was significant for multiple habitats. The observed step-lengths were significantly longer than random steps in the forest habitat ($\beta = 0.0092$, $p = 0.043$), whereas they were marginally significant in agriculture ($\beta = 0.0077$, $p = 0.077$) and scrubland/fallow habitat ($\beta = 0.0079$, $p = 0.075$). Overall, although there was no significant preference or avoidance of habitat classes apart from anthropogenic ones, the movement speed in each class was substantially different, with dogs moving with the longest step lengths of approximately 85m-90m in the forested areas (traversing longer distances between GPS fixes), followed by scrubland and

agricultural fields, where the step lengths were closer to 70m-75m (Fig. 5). The slowest movement with the shortest step length of 45-50m was recorded in settlements, and there was no significant difference when compared to random steps. Between villages, the movement trend was similar in both, but the movement speed was marginally higher in Moyar across all habitat classes (Fig. 5).

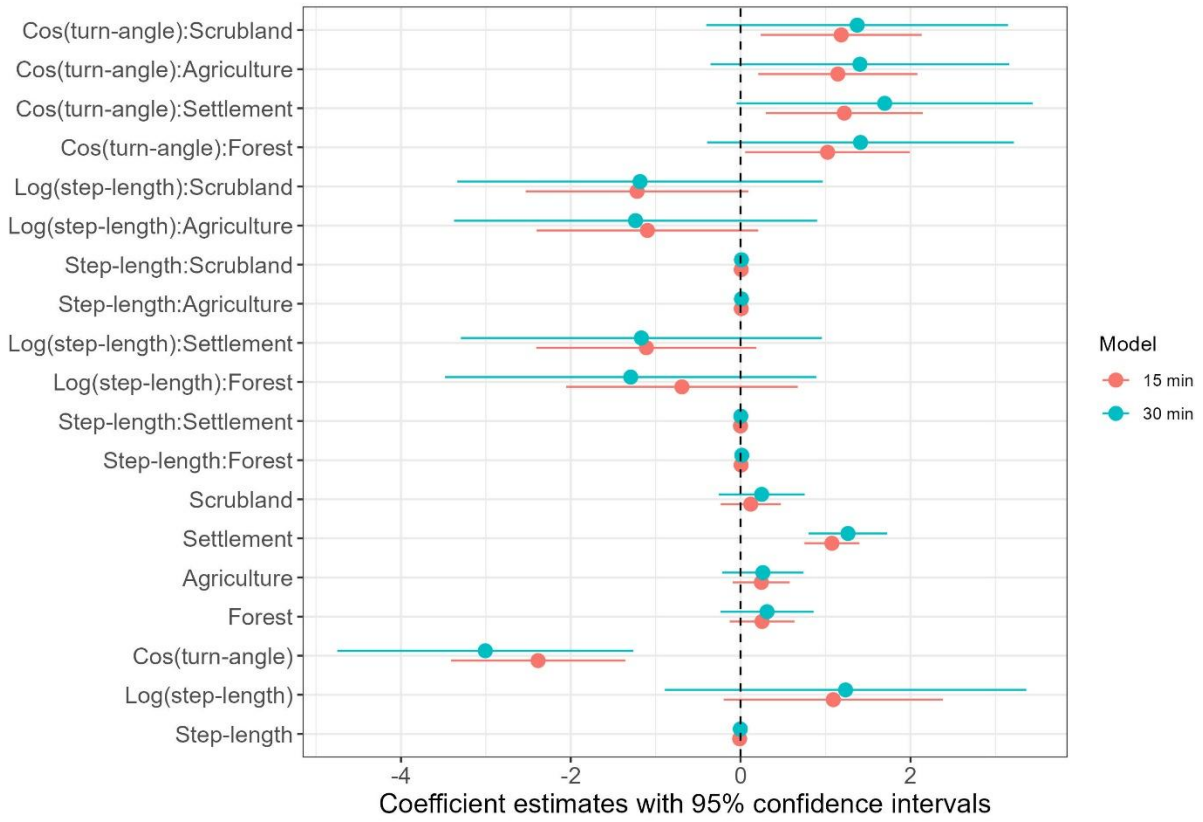

Figure 4: Coefficient estimates from the integrated step-selection analysis for the two different temporal scales. The orange dots represent the model where the temporal scale for consecutive fixes was resampled at 15 minutes, and the green dots represent the model where the temporal scale for consecutive fixes was resampled at 30 minutes.

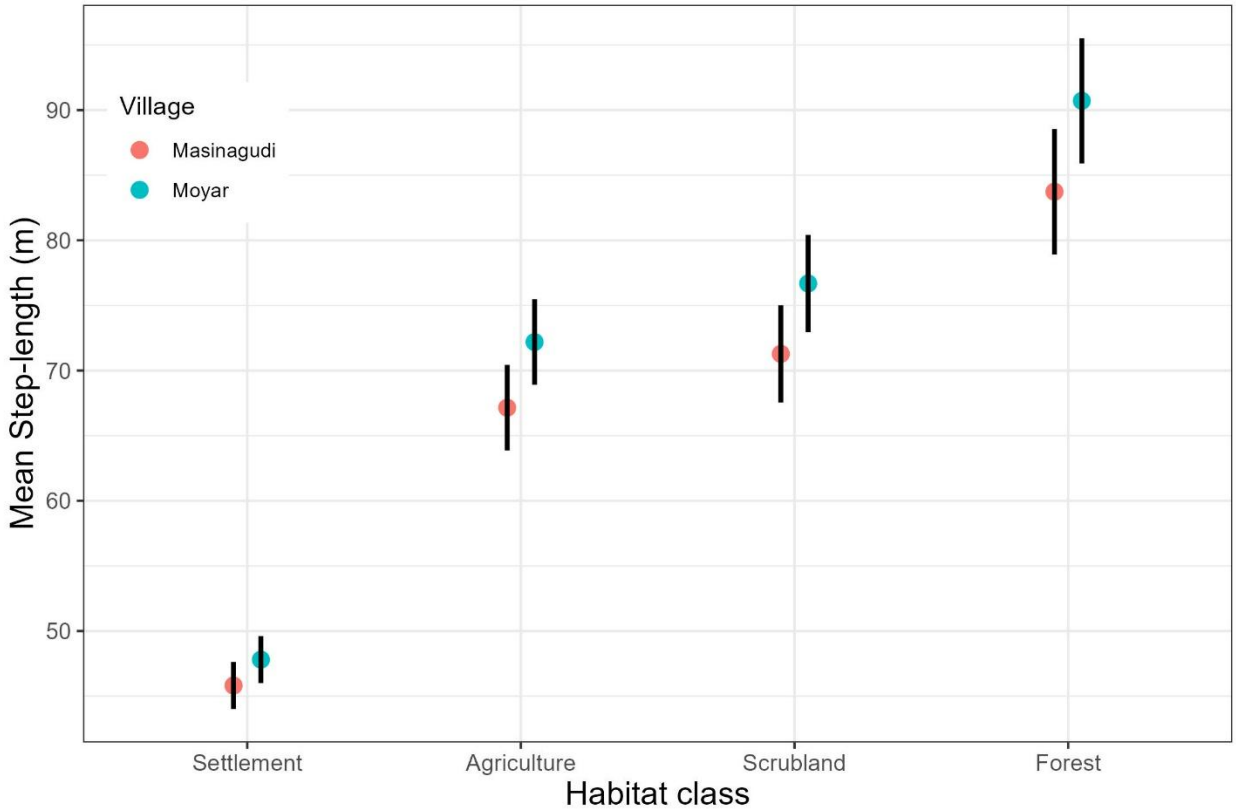

Figure 5: Estimates of mean step length (speed) for movement estimated for different habitats and different villages derived using the integrated step-selection function.

Discussion

Our study investigates the movement ecology of 15 owned free-ranging domestic dogs in Mudumalai Tiger Reserve, India. We found that dogs usually stayed close to their homes, with the vast majority of recorded locations remaining within 500m of the owner's house, limiting their potential for significant ecological impact. The best fit model for all individuals was OU anisotropic, indicating directionally dependent home-ranging behaviour. The activity range for most dogs was smaller than 10 hectares, and while it ranged from smaller than 5 ha to higher than 25 ha across individuals, this variation was relatively low compared to the findings of

similar studies, where activity ranges as low as 0.78 ha and as high as 509 ha have been documented [19]. The maximum distance from home travelled by a dog (1197m) was fairly short compared to ranging distance in other areas like Cambodia (up to 4km) [19] and Australia (8-30km) [14], and was similar to the distance travelled in Chile (0.5-1.9km) [46]. Given their fairly restricted movement patterns, these dogs seem to fall under the class of *stay-at-home* dogs, according to the three classes defined by Hudson et al. (2017). They display minimal roaming and are likely to have the majority of the requirements fulfilled at or close to their home, by the humans they depend on [13]. The range and median of activity ranges are similarly on the lower side of activity ranges recorded elsewhere [19] (See also Supplementary Table S2).

Estimates of movement metrics (the activity range, mean distance to home, and intensity of use), when compared based on village, sex of the dog, and day/night, showed no significant difference apart from intensity of use, which was significantly different between villages (Table 2, Fig. 3). We did not expect any sex-based differences with respect to any of these metrics, given that all dogs were neutered or spayed except one male. Additionally, though neutered males have been recorded as having significantly larger activity ranges than spayed females elsewhere [47], we did not find that to be true here (Table 2). The lack of significant difference between day and night mean distance from home was unexpected, as we expected that dogs would move less at night to minimize chances of encountering wildlife that are more active at village boundaries at night (such as elephants or leopards). The lack of difference between day and night may be a product of the short sampling period, or it may be due to the fact that we defined ‘night’ as post 1800 hours, when dogs might still be quite active for a few hours post sunset (16) or well into the night (17).

The significant difference in intensity of use between villages, however, indicates that dogs use their activity ranges differently in each village, despite the similarity in the size of the area used. In Moyar, the human population is small and village homes are divided into clusters of settlements separated by large stretches of agricultural land. In Masinagudi, however, the human population is several times larger and agricultural patches are isolated by well-connected roads and densely constructed houses. Therefore, we interpret the higher intensity of use by dogs in Moyar as a pattern of movement restricted to safe, well-known areas, with minimal forays to novel areas with higher risk of wildlife encounters. This is likely due to the heightened risk posed by wildlife to dogs, stemming from two factors: the smaller human population with fragmented clusters of settlements, and the larger, more porous perimeter with the forest and swathes of empty land inside the village that are conducive to wild animal movement. Indeed, spotted deer, wild pigs, elephants, and a leopard have previously been camera trapped inside Moyar (SVK, unpub. data). That these free-ranging dogs adapted different roaming behaviours depending on their village of origin, even when the two study sites were situated within 5km of each other, indicates a high degree of behavioural plasticity.

This interpretation is also supported by the habitat use and integrated step selection analysis results. We found that dogs mostly use human-modified land types, primarily settlement and agricultural land, with only 3.05% of all fixes located in the protected area. This is similar to previous findings in India [30], Chad [36] and Chile [17,46]. The results of the step selection analysis are also similar to previous studies [17,48], where anthropogenic habitats were found to be the most preferred habitat type. Although dogs did not significantly prefer or avoid any

habitat type except settlements, which were highly preferred, the difference in step length, or movement speed, in these habitats (Fig. 5) reflected how dogs used them. Forest areas were traversed almost twice as fast as settlements, and about 1.2 times as fast as agricultural or scrubland areas. This indicates that forest areas were used in a utilitarian manner, solely for movement (perhaps exploratory forays or travel between points) while settlements were used for rest or play. Movement in agricultural and scrubland areas may have been while accompanying humans, as all the dogs in this study were owned. Additionally, the higher movement speed in Moyar, where the human population was smaller and more fragmented, while not statistically significant, highlights how human use of wildlife-adjacent land can closely influence the movement patterns of domestic commensals like dogs. While previous studies [e.g., 17, 46] have reported on free-ranging dog habitat usage, utilizing the robust framework of integrated step-selection analysis to model dog habitat selection allowed us to compare free-ranging dog movement between two sites at a fine geographical scale, presenting further support for the human-shield hypothesis [49]. Our findings not only contribute to dog movement and behavioural ecology, but suggest that this movement - and therefore potential impact on wildlife - can differ significantly within villages in the same landscape, a nuance that should be taken into consideration when designing, implementing and monitoring dog management strategies that aim to curb roaming behaviour.

Fieldwork for this study was primarily limited by logistic and technological difficulties, namely the unauthorized removal and subsequent loss of collars (as people were apprehensive about the negative repercussions of their dogs being tracked) and collar malfunction errors resulting in data loss. These issues reduced our effective sample size from 26 dogs to 15 dogs. We were also

unable to collar truly feral or unowned dogs, which are most likely to range into the forest alone, as this would have required chemical immobilization by a veterinarian. We were therefore unable to differentiate dog movement in the presence versus absence of humans. Though this also constrained the diversity of our sample pool, our findings provide valuable insight into the movement of sterilized and owned free-ranging dogs, which comprises the vast majority of the large dog population in the Sigur Plateau region of Mudumalai Tiger Reserve (SVK, unpub. data). They also provide a standard of comparison to evaluate the impact of sterilization programmes on dog movement patterns. Lastly, the duration of sampling [up to ten days per dog and approximately two months overall) was relatively short when compared to other, similar studies [see Supplementary Table S2). This was a disadvantage, as dog movement may differ significantly across seasons [36), while this study was limited to a single season study.

Conclusion

In summary, this study reveals that while coarse indices of movement such as dog activity range remained limited and showed no significant difference between the two villages studied, habitat use differed as a potential consequence of human presence and habitation providing a shelter effect. Our findings suggest that owned free-ranging dogs, specifically those sterilized and provisioned by their owners, may pose a relatively low risk to wildlife in Mudumalai Tiger Reserve in terms of the size of area used and time spent in the forest. We therefore recommend that the programmes carried out by local animal welfare NGOs be sustained in the long term with a stronger push to sterilize and vaccinate feral dogs as well, ideally with consistent financial and logistical support from relevant local government bodies. While the limited scale of this study does not allow for direct extrapolation to other regions, it supports the idea that local

context is highly relevant to dog ecology [9], indicating the need for further studies from a broad range of socio-ecological contexts. In general, research on the fundamental ecology of free-ranging dogs at the human-wildlife interface is of vital importance in order to effectively mitigate dog-wildlife conflict.

For future studies, we recommend collaring more broadly across dog demographics (namely ownership, sex, age and sterilization status) as well as across human and village related parameters (e.g., length of the village-forest perimeter, household density, agricultural cover) at larger spatial and temporal scales. In particular, studies from non-protected areas that support wildlife may not only be easier to carry out but may provide much-needed insight into the dog-wildlife interface in areas with no restrictions on human movement and land use.

Declarations

Ethics approval and consent to participate

All GPS collars were fitted with the owners' consent, and often by the owners themselves. Collars were within required weight limits (<250 grams) and caused no physical distress to dogs during the duration of deployment.

Consent for publication

Not applicable

Availability of data and materials

The dataset generated during this study is available in the Movebank repository under the study name "Free-ranging dogs - vksanj - Mudumalai TR - GPS collaring", study ID 5328251712, at

the following link - https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study5328251712

Codes for data analysis are available on Github at the following link - https://github.com/nilanjanchatterjee/Dog-population-and-movement-Analysis/blob/main/02_Movement_analysis.html

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

SVK acquired funding for the study, conducted fieldwork, participated in data analysis, and drafted the manuscript. NC led data analysis and contributed to manuscript writing. RK provided logistic and supervisory support, and contributed to manuscript writing. All authors read and approved the final manuscript.

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References

465 1. Gompper ME. The dog-human-wildlife interface: assessing the scope of the problem. In:
466 Free-ranging dogs and wildlife conservation. 1st ed. OUP Oxford; 2014. p. 9–54.

467 2. Ortolani A, Vernooij H, Coppinger R. Ethiopian village dogs: Behavioural responses to a
468 stranger's approach. Appl Anim Behav Sci. 2009 Jul 1;119(3):210–8;
469 doi:10.1016/j.applanim.2009.03.011.

470 3. Acosta-Jamett G, Cleaveland S, Cunningham AA, Bronsvoort BM deC. Demography of
471 domestic dogs in rural and urban areas of the Coquimbo region of Chile and implications for
472 disease transmission. Prev Vet Med. 2010 May;94(3–4):272–81;
473 doi:10.1016/j.prevetmed.2010.01.002.

474 4. Butler JRA, Bingham J. Demography and dog-human relationships of the dog population in
475 Zimbabwean communal lands. Vet Rec. 2000 Oct;147(16):442–6; 10.1136/vr.147.16.442.

476 5. Fiorello CV, Noss AJ, Deem SL. Demography, Hunting Ecology, and Pathogen Exposure of
477 Domestic Dogs in the Isoso of Bolivia. Conserv Biol. 2006 Jun;20(3):762–71;
478 doi:10.1111/j.1523-1739.2006.00466.x.

479 6. Kitala P, McDermott J, Kyule M, Gathuma J, Perry B, Wandeler A. Dog ecology and
480 demography information to support the planning of rabies control in Machakos District,
481 Kenya. Acta Trop. 2001 Mar 30;78(3):217–30; doi:10.1016/S0001-706X(01)00082-1.

482 7. Twardek WM, Peiman KS, Gallagher AJ, Cooke SJ. Fido, Fluffy, and wildlife conservation:
483 The environmental consequences of domesticated animals. Environ Rev. 2017
484 Dec;25(4):381–95; doi:10.1139/er-2016-0111.

485 8. Young JK, Olson KA, Reading RP, Amgalanbaatar S, Berger J. Is Wildlife Going to the
486 Dogs? Impacts of Feral and Free-roaming Dogs on Wildlife Populations. BioScience. 2011
487 Feb 1;61(2):125–32; doi:10.1525/bio.2011.61.2.7.

488 9. Gompper ME. Adding Nuance to Our Understanding of Dog–Wildlife Interactions and the
489 Need for Management. Integr Comp Biol. 2021 Jul 1;61(1):93–102;
490 doi:10.1093/icb/icab049.

491 10. Doherty TS, Dickman CR, Glen AS, Newsome TM, Nimmo DG, Ritchie EG, et al. The
492 global impacts of domestic dogs on threatened vertebrates. Biol Conserv. 2017 Jun
493 1;210:56–9; doi:10.1016/j.biocon.2017.04.007.

494 11. Dürr S, Dhand NK, Bombara C, Molloy S, Ward MP. What influences the home range size
495 of free-roaming domestic dogs? Epidemiol Infect. 2017 May;145(7):1339–50;
496 doi:10.1017/S095026881700022X.

497 12. Dürr S, Ward MP. Roaming behaviour and home range estimation of domestic dogs in
498 Aboriginal and Torres Strait Islander communities in northern Australia using four different
499 methods. Prev Vet Med. 2014 Nov 15;117(2):340–57; doi:10.1016/j.prevetmed.2014.07.008.

500 13. Hudson EG, Brookes VJ, Dürr S, Ward MP. Domestic dog roaming patterns in remote
501 northern Australian indigenous communities and implications for disease modelling. Prev
502 Vet Med. 2017 Oct 1;146:52–60; doi:10.1016/j.prevetmed.2017.07.010.

503 14. Meek PD. The movement, roaming behaviour and home range of free-roaming domestic
504 dogs, Canis lupus familiaris, in coastal New South Wales. Wildl Res. 1999;26(6):847–55;
505 doi:10.1071/wr97101.

15. Molloy S, Burleigh A, Dürr S, Ward M. Roaming behaviour of dogs in four remote Aboriginal communities in the Northern Territory, Australia: preliminary investigations. Aust Vet J. 2017;95(3):55–63; doi:10.1111/avj.12562.

16. Sparkes J, Körtner G, Ballard G, Fleming PJS. Spatial and temporal activity patterns of owned, free-roaming dogs in coastal eastern Australia. Prev Vet Med. 2022 Jul 1;204:105641; doi:10.1016/j.prevetmed.2022.105641.

17. Schüttler E, Saavedra-Aracena L, Jiménez JE. Spatial and temporal plasticity in free-ranging dogs in sub-Antarctic Chile. Appl Anim Behav Sci. 2022 May 1;250:105610; doi:10.1016/j.applanim.2022.105610.

18. Muinde P, Bettridge JM, Sousa FM, Dürr S, Dohoo IR, Berezowski J, et al. Who let the dogs out? Exploring the spatial ecology of free-roaming domestic dogs in western Kenya. Ecol Evol. 2021;11(9):4218–31; doi:10.1002/ece3.7317.

19. Ladd R, Meek P, Eames JC, Leung LKP. Activity range and patterns of free-roaming village dogs in a rural Cambodian village. Wildl Res. 2023 Jul;51(1); doi:10.1071/WR23024.

20. Pérez GE, Conte A, Garde EJ, Messori S, Vanderstichel R, Serpell J. Movement and home range of owned free-roaming male dogs in Puerto Natales, Chile. Appl Anim Behav Sci. 2018 Aug 1;205:74–82; doi:10.1016/j.applanim.2018.05.022.

21. Ruiz-Izaguirre E, van Woersem A, Eilers K (c.) H a. M, van Wieren SE, Bosch G, van der Zijpp AJ, et al. Roaming characteristics and feeding practices of village dogs scavenging sea-turtle nests. Anim Conserv. 2015;18(2):146–56; doi:10.1111/acv.12143.

526 22. Belsare A, Vanak AT. Modelling the challenges of managing free-ranging dog populations.
527 Sci Rep. 2020 Nov 2;10(1):18874; doi:10.1038/s41598-020-75828-6.

528 23. Reddy CS, Sreelekshmi S, Jha CS, Dadhwal VK. National assessment of forest
529 fragmentation in India: Landscape indices as measures of the effects of fragmentation and
530 forest cover change. Ecol Eng. 2013 Nov 1;60:453–64; doi:10.1016/j.ecoleng.2013.09.064.

531 24. Venkataraman K, Sivaperuman C. Biodiversity Hotspots in India. In: Sivaperuman C,
532 Venkataraman K, editors. Indian Hotspots: Vertebrate Faunal Diversity, Conservation and
533 Management Volume 1. Singapore: Springer; 2018. p. 1–27. Available from:
534 https://doi.org/10.1007/978-981-10-6605-4_1

535 25. Belsare AV, Vanak AT, Gompper ME. Epidemiology of Viral Pathogens of Free-Ranging
536 Dogs and Indian Foxes in a Human-Dominated Landscape in Central India. Transbound
537 Emerg Dis. 2014;61(s1):78–86; doi:10.1111/tbed.12265.

538 26. Mahar N, Habib B, Hussain SA. Do we need to unfriend a few friends? Free-ranging dogs
539 affect wildlife and pastoralists in the Indian Trans-Himalaya. Anim Conserv. 2024
540 Feb;27(1):53-64; doi: 10.1111/acv.12876.

541 27. Vanak AT, Thaker M, Gompper ME. Experimental examination of behavioural interactions
542 between free-ranging wild and domestic canids. Behav Ecol Sociobiol. 2009 Dec
543 1;64(2):279–87; doi:10.1007/s00265-009-0845-z.

544 28. Home C, Bhatnagar YV, Vanak AT. Canine Conundrum: domestic dogs as an invasive
545 species and their impacts on wildlife in India. Anim Conserv. 2018;21(4):275–82;
546 doi:10.1111/acv.12389.

29. Tiwari HK, Bruce M, O'Dea M, Robertson ID. Utilising Group-Size and Home-Range Characteristics of Free-Roaming Dogs (FRD) to Guide Mass Vaccination Campaigns against Rabies in India. Vaccines. 2019 Dec;7(4):136; doi:10.3390/vaccines7040136.

30. Vanak AT, Gompper ME. Interference competition at the landscape level: the effect of free-ranging dogs on a native mesocarnivore. J Appl Ecol. 2010;47(6):1225–32; doi:10.1111/j.1365-2664.2010.01870.x.

32. Suresh HS, Dattaraja HS, Sukumar R. Tree flora of mudumalai sanctuary, Tamil Nadu, Southern India. Indian For. 1996;122:507–19.

33. Aanensen DM, Huntley DM, Menegazzo M, Powell CI, Spratt BG. EpiCollect+: linking smartphones to web applications for complex data collection projects. F1000Research. 2014 Aug 20;3:199; doi:10.12688/f1000research.4702.1.

34. Fleming CH, Calabrese JM. ctmm: Continuous-Time Movement Modeling. 2023. Available from: https://github.com/ctmm-initiative/ctmm

35. R Core Team. R: a Language and Environment for Statistical Computing. (Internet]. Vienna, Austria.: R Foundation for Statistical Computing; 2021. Available from: https://www.R-project.org/

36. Wilson-Aggarwal JK, Goodwin CED, Moundai T, Sidouin MK, Swan GJF, Léchenne M, et al. Spatial and temporal dynamics of space use by free-ranging domestic dogs Canis familiaris in rural Africa. Ecol Appl. 2021;31(5):e02328; doi:10.1002/eap.2328.

37. Almeida PJAL, Vieira MV, Kajin M, Forero-Medina G, Cerqueira R. Indices of movement

behaviour: conceptual background, effects of scale and location errors. Zool Curitiba. 2010 Oct;27:674–80; doi:10.1590/S1984-46702010000500002.

38. Loretto D, Vieira MV. The Effects of Reproductive and Climatic Seasons on Movements in the Black-Eared Opossum (Didelphis aurita Wied-Neuwied, 1826). J Mammal. 2005 Apr 15;86(2):287–93; doi:10.1644/BEH-117.1.

39. Signer J, Fieberg J, Avgar T. Animal movement tools (amt): R package for managing tracking data and conducting habitat selection analyses. Ecol Evol. 2019;9:880–90.

40. Pebesma E. Simple Features for R: Standardized Support for Spatial Vector Data. R J. 2018;10(1):439–46.

41. Avgar T, Potts JR, Lewis MA, Boyce MS. Integrated step selection analysis: bridging the gap between resource selection and animal movement. Methods Ecol Evol. 2016;7(5):619–30; doi:10.1111/2041-210X.12528.

42. Muff S, Signer J, Fieberg J. Accounting for individual-specific variation in habitat-selection studies: Efficient estimation of mixed-effects models using Bayesian or frequentist computation. J Anim Ecol. 2020;89(1):80–92; doi:10.1111/1365-2656.13087.

43. Chatterjee N, Wolfson D, Kim D, Velez J, Freeman S, Bacheler NM, et al. Modelling individual variability in habitat selection and movement using integrated step-selection analysis. Methods Ecol Evol. 2024;15(6):1034–47; doi:10.1111/2041-210X.14321.

44. Brooks ME, Kristensen K, Benthem KJ van, Magnusson A, Berg CW, Nielsen A, et al. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized

Linear Mixed Modeling. R J. 2017;9(2):378–400.

45. Wickham H. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York; 2016.

46. Sepúlveda M, Pelican K, Cross P, Eguren A, Singer R. Fine-scale movements of rural free-ranging dogs in conservation areas in the temperate rainforest of the coastal range of southern Chile. Mamm Biol. 2015 Jul 1;80(4):290–7; doi:10.1016/j.mambio.2015.03.001.

47. Sparkes J, Körtner G, Ballard G, Fleming PJS, Brown WY. Effects of Sex and Reproductive State on Interactions between Free-Roaming Domestic Dogs. PLOS ONE. 2014 Dec 26;9(12):e116053; doi:10.1371/journal.pone.0116053.

48. Cunha Silva L, Friker B, Warembourg C, Kanankege K, Wera E, Berger-González M, et al. Habitat selection by free-roaming domestic dogs in rabies endemic countries in rural and urban settings. Sci Rep. 2022 Dec 3;12(1):20928; doi:10.1038/s41598-022-25038-z.

Supplementary files

Data:

Table S1: Dog demographic data — Dog ID number, age, sex, sterilisation status, village of origin, number of fixes and days collared for each dog.

Table S2: Home/activity range comparisons from global studies — expanded table adopted from Ladd et al., 2023, with home/activity range estimates and sampling durations from dog telemetry studies across countries.

Table S3: ΔAIC comparison across activity range models — ΔAIC values for all trialled models during activity range estimation