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**Research Article**

# Spatial risk assessment and hotspot mapping of free-roaming dog bites in Tehran, Iran: A public health perspective

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## Abstract

Free-roaming dogs (FRDs) pose significant public health and ecological challenges in urban and rural landscapes, particularly in developing countries. In Tehran Province, Iran, the increasing frequency of FRD bites and their role as potential reservoirs for zoonotic diseases underscore the need for spatially explicit risk assessment. This study utilized the MaxEnt model to predict the spatial distribution of FRDs and identify high-risk areas for dog bites based on environmental and climatic variables. A dataset of 3,630 FRD bite incidents recorded for Tehran Province in 2023 was analyzed alongside 12 environmental and 6 climatic predictors. The model demonstrated high predictive accuracy (AUC = 0.934). Results highlighted distance to roads (74%) and distance to parks (12.1%) as the most important factors, while climatic variables played a secondary role. The spatial analysis revealed that high-risk areas are concentrated in the north (Districts 1 and 2), southern and eastern outskirts of Tehran City (e.g., Districts 15, 16, 19, and 20) and counties such as Qarchak, Varamin, and Pakdasht. Further hotspot analysis (Getis-Ord Gi) and LISA clustering confirmed significant spatial autocorrelation (Moran's I = 0.7; *p*-value $\leq 0.05$) and identified critical clusters for intervention. These findings provide valuable insights into the spatial dynamics of FRD bites, enabling policymakers to prioritize high-risk areas for population control measures, public awareness, and waste management improvements. Integrating these results into urban planning frameworks can mitigate public health risks, reduce human-dog conflicts, and promote sustainable FRD management strategies.

**Keywords:** Public Health, Free-roaming Dogs, Spatial Analysis, Risk Mapping, Rabies, Invasive species

## Introduction

The concept of biological invasion is a broad one with various dimensions that can be studied in both natural and human environments. The domestic dog (*Canis lupus familiaris* Linnaeus, 1758), is a subspecies of the grey wolf with unique behavioral characteristics, demonstrate remarkable adaptability and flexibility for survival. However, their invasion as a pest in urban and human environments poses significant threats, particularly by causing damage to human interests. The public health threats posed by free-roaming dogs (FDRs) are a serious issue in Iran, imposing substantial financial and health burdens on both the public and the government. The global domestic dog population is estimated to be around 700 million, with some areas reporting dog populations exceeding human populations (Hughes & Macdonald, 2013). This phenomenon is particularly evident in developing countries, where FRD populations are disproportionately high, especially in urban areas. Contributing factors include inadequate animal control policies, cultural norms surrounding dog ownership, and favorable environmental conditions that facilitate uncontrolled breeding (Smith et al., 2019). Approximately, 75% of the global domestic dog population is considered free-roaming (Vanak & Gompper, 2009; Hughes & Macdonald, 2013). FRD bites constitute a significant global public health concern. In Iran, dogs are responsible for the majority of animal bite incidents. Each year, over 150,000 animal bite cases are reported, with dogs accounting for 94% of these cases (Abbasi et al., 2017; Abedi et al., 2019).

The negative consequences of FRDs and their increasing population can be categorized into multiple aspects. First, and foremost are the health and hygiene impacts, which can be further divided into physical and psychological effects (Fernandes et al., 2023). Domestic dogs are carriers of several zoonotic diseases that pose serious threats to humans, livestock, and wildlife (Morters et al., 2014; Smith et al., 2019). Among the most critical is rabies, a fatal viral disease (Gholami et al., 2014; Tarantola et al., 2019). Additionally, FRDs can transmit a range of viral and bacterial diseases, including hydatid disease, distemper, mange, tetanus, norovirus, salmonellosis, brucellosis, yersiniosis, campylobacteriosis, leptospirosis, and staphylococcal infections (Ghasemzadeh & Namazi, 2015).

Moreover, dogs act as significant reservoirs for leishmaniasis, particularly in urban environments, exacerbating public health challenges in affected regions (Quinnell, 2009). The persistence of these zoonotic threats highlights the urgent need for targeted interventions to address the health risks posed by FRDs and their interaction with human and animal populations.

A comprehensive metabarcoding analysis revealed the presence of multiple pathogenic bacteria and parasites in the feces of FRDs, including Campylobacter and Giardia, which were found to be significantly more prevalent in FRDs compared to domesticated pets (Liyanagama et al., 2024; Ali et al., 2023; Sharma, 2022; Feng et al., 2015). These pathogens are associated with gastrointestinal diseases and other severe health complications in humans who come into contact with infected animals or contaminated environments.

The public health implications of FRD bites go beyond immediate physical injuries, extending to broader challenges, such as the heightened risk of rabies transmission. Rabies continues to be a critical health issue in many regions, particularly those where the dog meat trade persists, as it can result in fatal infections if not promptly treated (Ubeyratne et al., 2018; Vural et al., 2024). These findings underscore the urgent need for effective FRD population management and enhanced public health measures to mitigate zoonotic risks.

From a public health perspective, dogs are responsible for over 99% of rabies virus transmissions to humans. Rabies is a deadly viral disease that affects the central nervous system, and once symptoms appear, it is invariably fatal, with a 100% mortality rate. Annually, approximately 60,000 people die from rabies, 40% of whom are children under the age of 15 (WHO, 2024). These fatalities predominantly occur in marginalized communities with limited access to vaccines and post-exposure prophylaxis (PEP) (Guo et al., 2018). In numerous studies published in Iran, dogs have been identified as the primary vector for the spread of the rabies virus in the country (Fayaz et al., 2011; Bashar, 2019). For example, Mazaheri et al. (2010), through an investigation of three northern provinces (Golestan, Mazandaran, and Gilan) during the years 2002 to 2007, reported that 91.3% of rabies cases (human and livestock) were attributed to dogs. While the physical health impacts are alarming, FRDs also pose significant mental health threats. Their presence in public area can lead to obsessive thoughts, a lack of mental security, and heightened psychological distress, particularly among children and women (Westgarth et al., 2024). This fear can restrict daily activities and lower individuals' quality of life (Boyd et al., 2004). Moreover, FRDs contribute to nuisances such as scavenging in garbage, spreading waste, damaging property, and incessant barking, especially in cities with inadequate control measures. From an economic perspective, the financial burden of dog bite treatment, including medical expenses, places substantial pressure on families and healthcare systems. Additionally, FRD attacks on livestock and property cause further economic losses, exacerbating the strain on affected individuals and communities. These combined physical, psychological, and economic impacts highlight the urgent need for comprehensive management strategies to mitigate the risks associated with FRDs.

The economic burden of post-exposure prophylaxis (PEP) in Asia is the highest worldwide, amounting to approximately $1.5 billion annually (Chen, 2021). Globally, the total economic cost of dog-mediated rabies is estimated at $8.6 billion, including expenses for prevention, control, and treatment measures (WHO, 2018). This substantial financial burden is driven by factors such as the high cost of vaccines, the complexity of multi-dose PEP protocols (which often require the administration of rabies immune globulin in severe exposure cases), limited healthcare accessibility, and inadequate surveillance systems.

To address this knowledge gap, we conducted a comprehensive study on FRDs in Tehran Province with the following objectives:

1. To identify the high-risk areas for dog biting incidents across the province.
2. To investigate the factors influencing the spatial distribution of FRDs.
3. To determine the districts within Tehran City that should be prioritized for control and management measures.

This study aims to provide actionable insights for policymakers and urban planners to mitigate the public health and ecological risks posed by FRDs while optimizing resource allocation for containment and management efforts.

## Material and methods

### Study area and dog bite data

Tehran Province, the most populous province in Iran with a population exceeding 16 million, is situated in the northern parts of the Iranian Plateau, covering an area of approximately 18,814 km$^2$ (Talkhabi et al., 2022) (Fig. 1). In addition to its high population density, Tehran Province (and Tehran City as the capital of Iran) is characterized by its industrial nature and a wide range of anthropogenic activities, making it an ideal setting for studying FRD bite incidents and their associated influencing factors. The public health challenges stemming from the dense population and complex landscape features of this region necessitated such an applied study to address the needs of both society and policymakers.

**Figure 1.** The location of study area within Iran.

Dog bite data for the year 2023 (1402 in the Iranian calendar) were obtained from the Ministry of Health and Medical Education (MOHME). The addresses associated with the bite incidents were processed and converted into geographical coordinates using the "geopy" package in the Google Colab platform after careful filtering and data cleaning. Given the presence of duplicate addresses, a custom Python script was utilized to disaggregate overlapping points by introducing a minimum spatial separation of five meters between each coordinate.

As a result, a dataset of 3,630 FRD bite incidents was compiled for Tehran Province for the study year. Additionally, geographic data for Tehran Province were sourced from the datagis.ir platform, while climatic data were obtained from the WorldClim database to supplement the analysis. This combination of spatial, environmental, and bite incident data provided a robust foundation for analyzing the dynamics of FRD bites and identifying key factors affecting their distribution within Tehran Province.

## Environmental and climatic variables

To identify the key variables influencing the distribution of FRDs and subsequent dog bites, 12 environmental variables were selected based on expert opinions. To eliminate redundant variables, reduce errors, and improve predictive accuracy, a Pearson correlation test was performed on the 19 climatic variables at a 75% significance level using IBM SPSS Statistics

(Ver. 19). Following this test, the number of climatic variables was reduced to six. (Table 1). A cell size of 30 meters was used for all variables.

**Table 1.** Variables used in the MaxEnt model.

| Variable | Description (abbreviation) | Unit |
|---|---|---|
| Topographic | Altitude: Elevation above sea level (dem_utm) | m |
| Cover-Use | Distance to roads (roads_dis) | Degrees |
| | Distance to parks (park_polygon_dis) | |
| | Distance to villages (village_dis) | |
| | Distance to residential areas (residential_dis) | |
| | Distance to suburb (suburb_dis) | |
| | Distance to landfill (recycling_dis) | |
| | Distance to gas stations (fuel_dis) | |
| | Distance to restaurants (restaurant_dis) | |
| | Distance to industrial parks (industrial_dis) | |
| | Distance to picnic sites (picnic_dis) | |
| | Population Density (population_density) | |
| Bioclimatic | Annual Mean Temperature (Bio1) | ℃ |
| | Isothermality (Bio3) | |
| | Temperature Annual Range (Bio7) | |
| | Mean Temperature of Warmest Quarter (Bio10) | |
| | Mean Temperature of Coldest Quarter (Bio11) | |
| | Precipitation Seasonality (Coefficient of Variation) (bio15) | mm |

## Distribution modeling and hotspot analysis

Three approaches were used to map high-risk areas for dog bites and the subsequent risk of rabies transmission. MaxEnt modeling (Ver. 3.4.4) was applied to predict distribution areas and suitable habitats for FRDs, as it is a powerful tool for identifying factors that affect the occurrence of species. The output from the MaxEnt model was then processed in GeoDa 1.22 software to perform LISA clustering for analyzing the spatial ecological quality of urban and rural areas, providing deeper insights into high-risk zones. Another analysis involved using Getis-Ord Gi hotspot analysis in ArcGIS 10.5 software, which utilizes Moran's I functions to determine where dog bite incidents show the highest concentration and proximity to each other.

For the MaxEnt classification of Tehran Province, due to its public health implications, the map was classified into two categories: low-risk and high-risk. To explore more detailed patterns within the 22 districts of Tehran City, the classification was expanded to four categories based on the maximum test sensitivity threshold from MaxEnt:

- Low Risk (0–0.293),
- Moderate Risk (0.293–0.528),
- High Risk (0.528–0.764),
- Very High Risk (0.764–1).

This classification enables more precise identification of areas within Tehran city that require immediate attention for controlling FRD populations and preventing health risks.

## Results

After running the model, the area under the curve (AUC) for the training data was 0.934 and for the test data was 0.931, indicating high accuracy and reliable performance of the model. Among all the variables used in the model, distance to roads had the highest contribution (74%), followed by distance to parks (12.1%) in the jackknife chart, indicating that these were the most effective factors for predicting the distribution (Table 2).

**Table 2.** Relative contributions of the environmental variables to the MaxEnt model.

| Variable | Percent contribution | Permutation importance |
|---|---|---|
| roads | 74 | 78.1 |
| parks | 12.1 | 7 |
| villages | 3.9 | 3.1 |
| residential | 3.3 | 1.6 |
| Bio 10 | 1.8 | 0 |
| restaurants | 1.1 | 3 |
| suburb | 0.9 | 1.9 |
| Bio 3 | 0.9 | 0 |
| population density | 0.6 | 0.7 |
| elevation | 0.3 | 1.3 |
| landfill | 0.2 | 0.2 |
| bio 1 | 0.2 | 0.2 |
| bio 15 | 0.2 | 0 |
| bio 7 | 0.1 | 0.3 |
| bio 11 | 0.1 | 2.2 |

| | | |
|---|---|---|
| picnic sites | 0.1 | 0 |
| gas stations | 0.1 | 0.4 |
| industrial park | 0.1 | 0 |

The suitable areas for dog distribution were predominantly observed in the north (Districts 1 and 2), southern and eastern outskirts of Tehran, such as Districts 15, 16, and parts of Districts 19 and 20, as well as in counties like Qarchak and Varamin. The jackknife chart, which illustrates the contribution of variables in constructing the predictive model, is shown in Figure 2. The map of suitable areas for FRD presence and biting is shown in Figure 3, the area and percentage classified as low-risk and high-risk for Tehran Province are 12,165.5 km$^2$ (~ 90.65%) and 1,253.886 km$^2$ (~ 9.35%) respectively. According to the model's output, Tehran County exhibited the largest suitable areas for biting and occurrence.

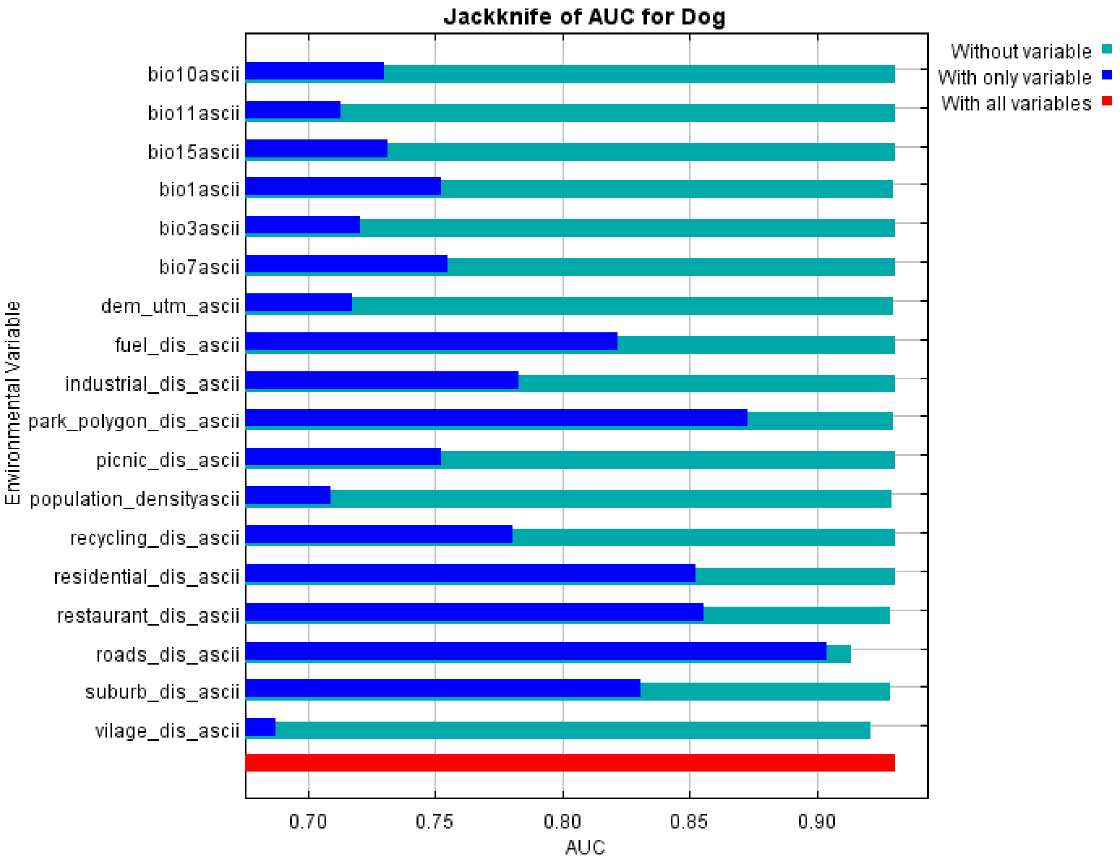

**Figure 2.** The relative predictive power of different environmental variables based on the Jackknife of area under the curve of response in the MaxEnt model for *C. l. familaris*.

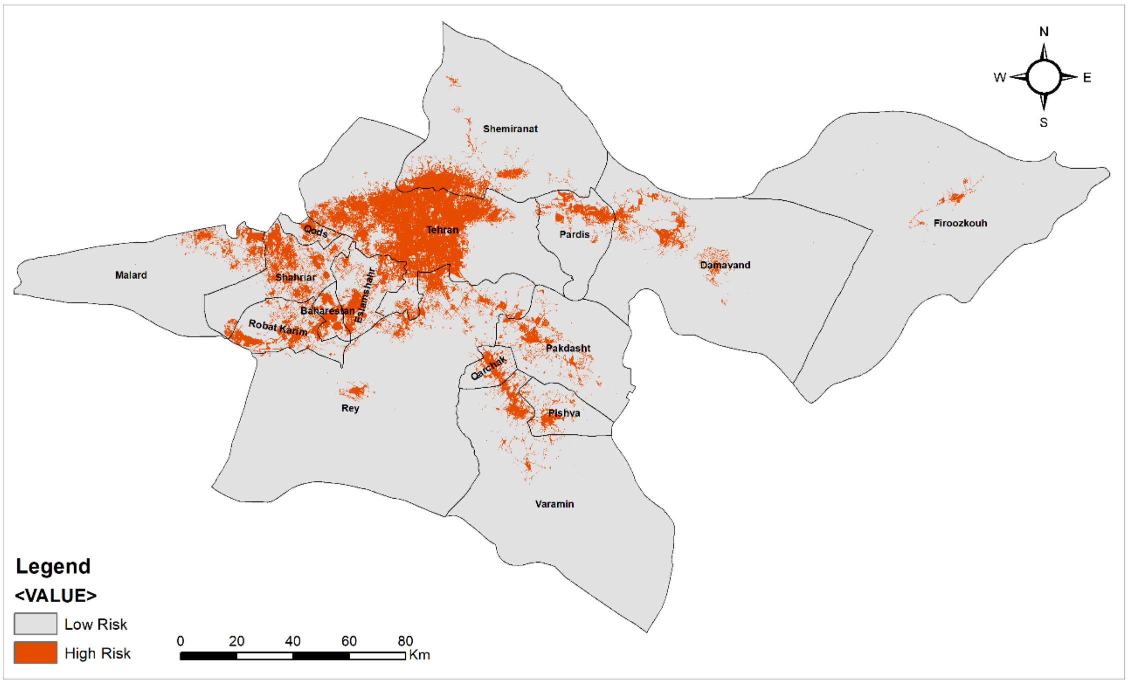

**Figure 3.** The classified map of MaxEnt model for *C. l. familaris* in 2023.

The LISA clustering map in GeoDa software is shown in Figure 4, with statistical significance and scatter plots displayed in Figure 5. The Moran's I value of 0.704 indicates a significant positive spatial correlation, emphasizing the presence of distinct clusters in geographic areas. This analysis identifies High-High clusters as priority areas for management and control, while Low-Low clusters are identified as regions with low potential for crisis. The classification helps to pinpoint areas with high ecological quality for dogs that are surrounded by other high-quality areas, and areas with low ecological quality surrounded by other low-quality areas. This categorization aids in precisely identifying environmental hot and cold spots within urban settings.

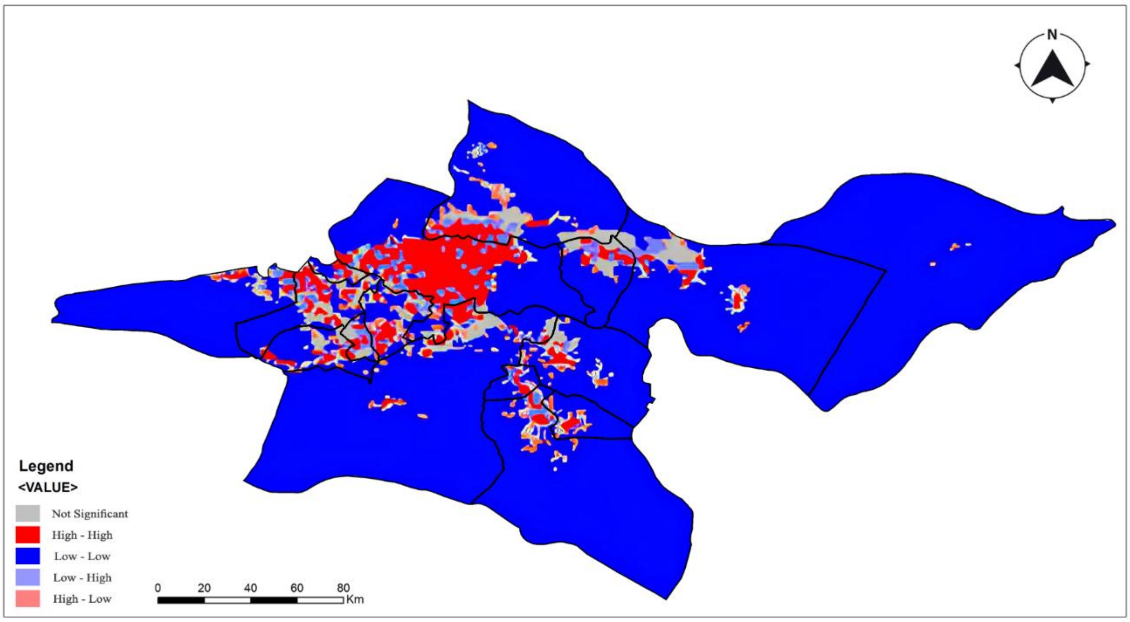

**Figure 3.** LISA risk map for dog bites in 2023.

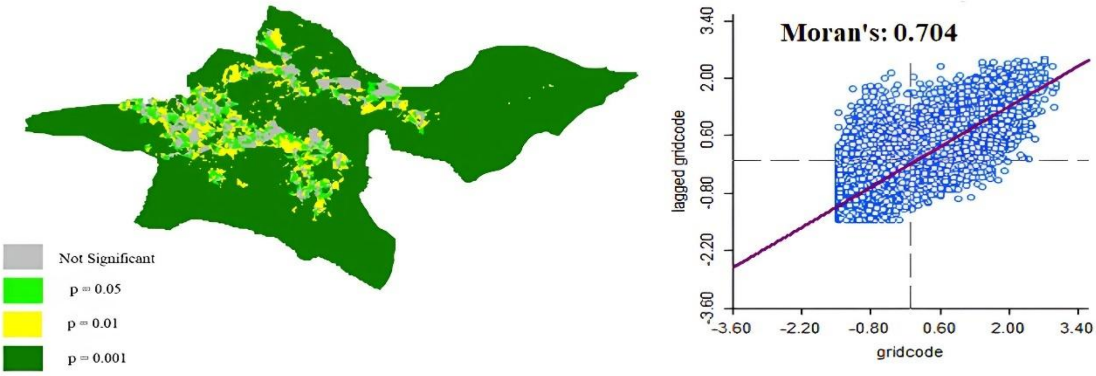

**Figure 4.** Statistical significance map of LISA and Moran's scatter plot of Tehran Province for dog bite risk areas in 2023.

The hotspot analysis of bite points in ArcGIS is shown in Figure 6, revealing that the counties of Qarchak, Varamin, and Pakdasht are the hottest regions in terms of bite frequency and intensity. Areas with Z-scores greater than 2.58 are identified as strong hotspots. The Moran's I value of 0.795 and a *p*-value < 0.001 indicate strong spatial clustering of bite points, with significant concentrations in the southern areas of Tehran. Based on the generated map, the northern parts of Tehran, such as Shemiranat and District 1, as well as the northwestern suburbs, which are more mountainous, were identified as cold spots.

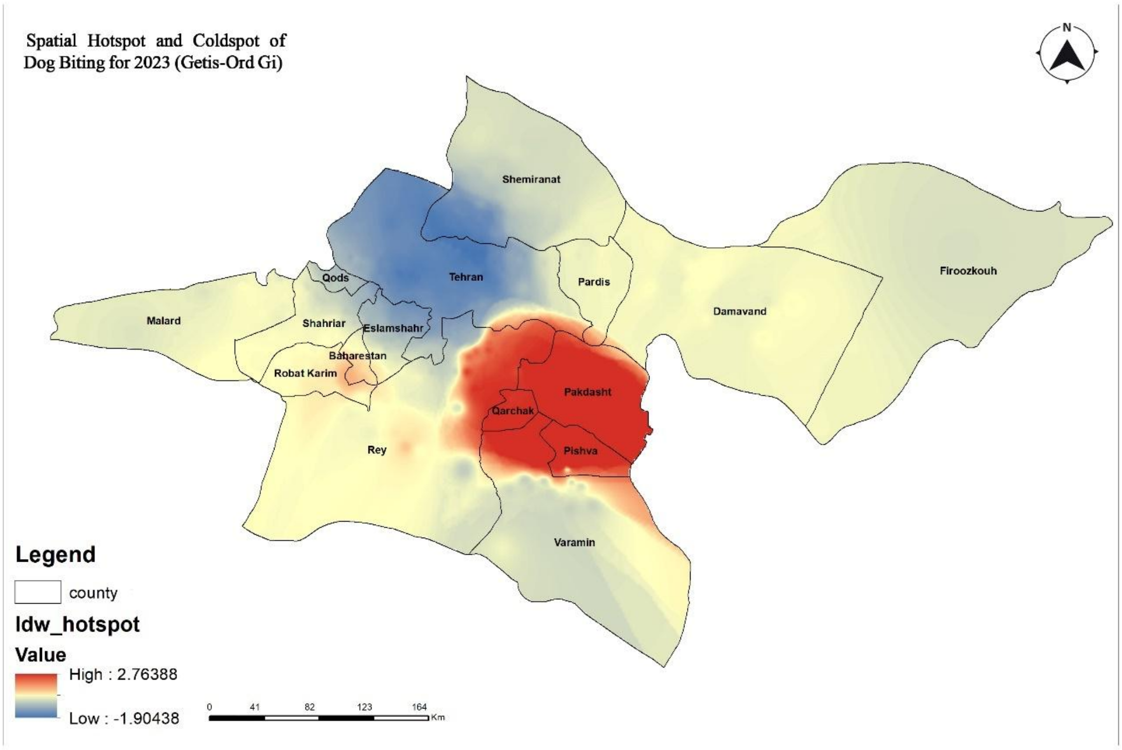

**Figure 5.** Hotspot-coldspot map of dog bite points in Tehran Province in 2023.

These results provide a clear spatial understanding of high-risk areas for FRD bites and their management priorities, contributing to more targeted and efficient control measures.

## Discussion

Annually, an estimated 60,000 human deaths from rabies occur worldwide (Fooks et al., 2019). The cost of each vaccine dose varies significantly depending on the type, ranging from $10 to $54. Given that individuals bitten by FRDs typically require five doses, the financial strain on affected individuals and healthcare systems is significant (Wambura et al., 2019; Hatam et al., 2013). According to the study by Farahtaj et al. (2014), approximately 1.2 million doses of rabies vaccine were imported into Iran between 2002 and 2011, with the incidence rate of rabies caused by FRDs calculated at 20 to 90 cases per 100,000 people during this period. Mostafavi et al. (2020) provided updated statistics, reporting an incidence rate of 180 cases per 100,000 people and highlighting that in 2016 alone, more than 170,000 animal bite cases were reported in the country. This situation led to the allocation of a 2000-billion-Rials budget for purchasing rabies vaccines and immunoglobulin serum. According to the director of the Rabies Division at the Pasteur Institute of Iran, approximately €18 million is spent annually on rabies vaccination costs in the country. These economic challenges highlight the urgent need for cost-effective, accessible rabies prevention and control strategies to mitigate the devastating financial and human toll of the disease.

The negative impacts of FRDs can also be analyzed from ecological and socio-cultural perspectives. Ecologically, FRDs contribute to issues such as competition with native wildlife, predation, behavioral changes in wild species, disease transmission, hybridization, and ultimately, alterations in the structure and functioning of ecosystems (Newsome et al., 2013; Doherty et al., 2017; Home et al., 2017). For instance, in a review study conducted by Nayeri et al. (2021), which analyzed media reports over a 20-year period, more than 160 incidents of dog attacks on Iranian mammal species were documented. These attacks were reported across 22 of Iran's 31 provinces, involving 17 different wildlife species.

The most frequently reported cases included attacks on the Asiatic cheetah (*Acinonyx jubatus venaticus*) (19 cases), Eurasian lynx (*Lynx lynx*) (18 cases), caracal (*Caracal caracal*) (10 cases), Pallas's cat (*Otocolobus manul*) (eight cases), and Persian gazelle (*Gazella subgutturosa*) (47 cases). Notably, 116 of these incidents occurred within protected areas, highlighting the critical ecological threat posed by FRDs to Iran's already vulnerable wildlife populations.

These findings emphasize the far-reaching impacts of FRDs, extending beyond public health to ecological degradation and disruption of wildlife conservation efforts, necessitating immediate and comprehensive management strategies (Bay et al., 2023). While the role of FRDs in rabies transmission in human-dominated landscapes is well-established, their broader health impacts in both human and natural environments remain poorly understood, particularly in Tehran Province, Iran. Effective management strategies require a fundamental understanding of FRD population dynamics and the environmental and socio-cultural factors that facilitate their dispersal and biting behaviors.

The results indicated that distance to roads, parks, villages, and residential areas had the greatest impact on the distribution, and subsequently, on dog attacks and bites. These findings are in accordance to Guo et al. (2018). Although these factors might seem logically evident without a statistical study, the model clearly underscores the importance of roads and parks in managing FRD populations. Roads serve as attractive pathways for FRDs, offering easy movement and access to human settlements or food sources (such as waste and discarded food typically found along roads). Dogs may also experience less competition at road edges, where access to resources is abundant. Similarly, parks appear to attract FRDs seeking shelter, quieter spaces, and food sources. The distance to villages (3.9%) may be significant due to inadequate management, providing quieter spots for shelter and access to food waste, while the distance from residential areas (3.3%) is related to access to food and shelter near these densely populated areas. Hence, areas close to roads and parks could be prioritized for FRDs population management and control efforts.

As expected, given that dogs are opportunistic animals with high adaptability, climatic variables played a secondary role and were not major factors in the model. Climatic variables, such as Mean Temperature of Warmest Quarter (Bio 10), indicate the role of warmer tempreture in influencing dog distribution, with higher biting incidents expected in warmer weather. Isothermality (Bio 3) reflects the potential impact of stable temperatures on dogs' seasonal behavior. Proximity to restaurants or gas stations, particularly near roads, is also crucial, as food waste may attract dogs to these areas.

The significant contribution of roads to the model suggests that these infrastructures not only effect the distribution of FRDs but could also be focal for managing populations. The differences observed between the MaxEnt model and the GIS hotspot analysis arise from the fact that MaxEnt identifies regions with suitable environmental conditions for FRD presence based on environmental variables and recorded dog bite data. For instance, northern Tehran, with higher living standards or less interaction between people and FRDs, has fewer dogs, although the presence of parks, green spaces, and suitable paths makes it favorable in the model. In contrast, GIS hotspot analysis is based on the actual distribution of dog bites, reflecting areas with more frequent incidents. MaxEnt, therefore, predicts suitable habitats, while GIS focuses on real-world interactions.

The LISA clustering analysis reveals that High-High clusters correspond to areas with high human populations, easy access to waste and food resources, and weak FRD management. These clusters are primarily located in the southern and southwestern parts of Tehran city, as well as the suburban and semi-industrial areas of Eslamshahr, Qarchak, Varamin, and Pakdasht. Low-Low clusters, on the other hand, are areas with lower bite incidents and are generally found in the western and northwestern parts of Tehran, which have lower population densities. High-Low and Low-High clusters are observed at the periphery of the hot clusters or in developing cities like Parand, Pardis, and suburban areas. These regions should be closely monitored to prevent the spread of high-risk clusters, and pilot control programs for FRDs are strongly recommended. This approach could not only reduce human-dog interactions but also lead to more sustainable management in similar areas.

The hotspots are driven by high access to food resources (e.g., waste or handouts from humans) and inadequate FRD management infrastructure. These areas are often linked with high human population densities, which increase the likelihood of human-dog interactions. From a spatial dynamic's perspective, hot clusters represent critical and stable points for human-dog interaction, whereas peripheral clusters could potentially evolve into new hotspots in the future.

In conclusion, focusing on the southern and eastern areas, such as Districts 1, 2, 15, 16, 19, and 20, and the counties of Varamin is crucial as they are identified as high-risk zones. (Fig. 7).

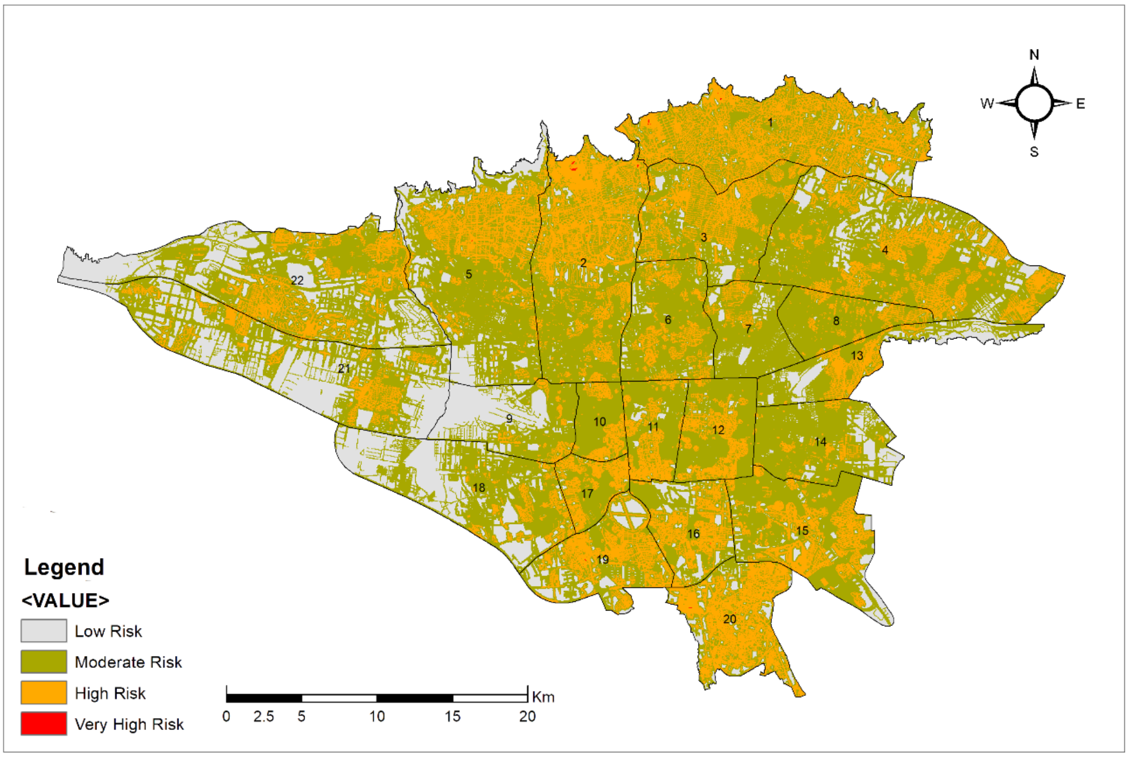

**Figure 5.** Suitable areas of free-roaming dogs in 22 Districts of Tehran City in 2023.

## Conclusion

Managing, controlling, and mitigating the negative impacts of species invasion require structured policies based on systemic thinking. Such policies should aim to achieve maximum benefits with minimal costs while addressing this critical challenge effectively. Given the high costs associated with neutering and vaccination programs, and to prevent the waste of financial resources, the most effective long-term solution would be to focus on educating the public on how to properly handle FRDs, as well as creating environments that discourage feeding and reduce food sources available to these animals. Establishing the necessary infrastructure for proper management requires time, financial investment, and specialized personnel. Therefore, the more feasible and practical approach, alongside building adequate management capacities, is the involvement and awareness of the public. Engaging the community in education and creating a shared responsibility for managing FRD populations will be a crucial and sustainable strategy moving forward.

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