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INDIRECT ASSOCIATION OF MONSOON RAINS WITH THE PATTERNS OF DOG-MEDIATED RABIES IN SRI LANKA

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SUMMARY: In many rabies endemic countries including Sri Lanka, dog populations are the main rabies reservoir and the main source of human infection. Understanding the ecology and spatiotemporal determinants of dog populations could inform targeted dog population control and rabies vaccination campaigns. Studies from India have postulated a positive association between monsoon rains and dog mating frequency, i.e., rainy season mating followed by a peak of births in the subsequent dry season, leading to an increase in the unvaccinated dog population. To test the hypothesis (positive association between rainfall patterns and reported rabies cases) in Sri Lanka, spatial and temporal patterns of dog and human rabies cases from 2004 through 2021 were analysed and compared with rainfall patterns in relation to Sri Lanka's three climate zones: wet, intermediate, and dry. Rabies cases were frequent in the highly populated south-west of the country, particularly in the wet zone. The study reveals an association between dog rabies cases and rainfall, with a notable increase in cases during the dry season across all three zones based on the Mann-Whitney U test. Hence, this suggests a seasonal variation in dog rabies incidence, potentially linked to rainy season mating followed by a peak of births in the subsequent dry season, among other potential factors. Hence, this supports the hypothesis of a potential rainfall-driven rise in the dog population. While further investigation is essential, this potential association of rainfall and fluctuations of dog populations could be considered in planning risk-based vaccination programmes, including spay-neuter programs for adult dogs (>1 year old), pre-rainy season vaccination and targeted vaccination of <1 year old pups soon after the end of the rainy season.

KEYWORDS: Rabies, Monsoon, Dog population, Spatiotemporal pattern, Sri Lanka, Epidemiology

INTRODUCTION

Despite international and local efforts to eliminate dog-mediated rabies, the disease remains endemic in the dog population in Sri Lanka, where dogs are the primary reservoir of the virus (Wimalaratne and Kodikara, 1999; Ubeyratne *et al*., 2018). In Sri Lanka, nearly 300,000 dog bites are reported annually, requiring post-exposure prophylaxis (PEP) to prevent rabies in the dog bite victims (Harischandra *et al*., 2016). Over 100,000 people receive post exposure prophylaxes annually (https://www.epid.gov.lk/case-of-afp) and government spends LKR 800 million annually which includes LKR 280 million for persons attacked by rabies infected stray dogs, and vaccination and sterilisation of dogs (https://www.newswire.lk/2025/05/22/rs-800-mn-spent-on-stray-dogs-annually-deputy-health-minister/). It is known that the dog population density and dynamic, dog ecology, dog rabies control strategies, responsible dog ownership, i.e. taking care of health, vaccination, dog birth control, providing shelter (Lembo *et al*., 2010), and human-dog interaction (Moore and Carpenter, 1999) play a role in the epidemiology of dog-mediated rabies. Prevention of rabies in humans requires effective management of rabies in the animal reservoir, including both owned and non-owned dogs (Zinsstag *et al*., 2007). The key recommendation is to vaccinate at least 70% of the dogs each year to maintain herd immunity (WHO, 2013). However, due to the high turnover within dog populations (high birth and death rates), maintenance of herd immunity in free roaming and stray dog populations can be challenging. Previous studies from South Africa and Indonesia demonstrate that this goal is attainable when consistent vaccination coverage is maintained at levels sufficient to preserve herd immunity, even in the presence of high dog population turnover (Morters *et al*., 2014; Conan *et al*., 2015).

Dog vaccination coverage in Sri Lanka increased steadily from 1970 to 2015. During this period, the number of suspected human rabies cases decreased (Harischandra *et al*., 2016), but reported dog rabies

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cases showed no corresponding decline (Karunanayake *et al*., 2014). Each year, data on dog bite incidents, rabies-positive dogs, and human rabies deaths are compiled by the National Reference Laboratory for Human and Animal Rabies Diagnosis and reported to the Public Health Veterinary Services Unit of the Ministry of Health, Sri Lanka. An update on the spatiotemporal patterns of rabies in Sri Lanka was published by Karunanayake *et al.* (2014), which includes yearly data from 1999 to 2010. The data showed a stable incidence of dog rabies cases over this time period (average 555.1) and a decline in the number of human rabies cases in the period 1999 to 2010, to 18-32 cases. According to previous estimates, the dog to human ratio in Sri Lanka was 1:8 in the 1980s (WHO, 1988), but no recent data are available to estimate the dog population size or the turnover rates. Thus, a better understanding of the association between variations in rabies cases and the underlying dog population dynamics, formed by direct factors (dog and human populations) and indirect factors (rainfall) would be useful for planning and implementing effective control strategies at both national and local levels.

Studies from India suggest a potential association between monsoon rains and increased dog mating frequency. Specifically, more mating occurred during the rainy season, leading to a peak in births observed during the subsequent dry season (Sen and Bhadra, 2015; Brill *et al.,* 2022). We argue that, if this association holds true for Sri Lanka, then this association could serve as a proxy for estimating the increase in the number of newborn pups susceptible to rabies during the dry season. This rise in young and susceptible dog population could potentially lead to weakening the herd immunity and potentially cause a seasonal increase in the number of rabies cases in both the dog population and in humans. Understanding this phenomenon in relation to the variations in space and time could support improving rabies prevention strategies, as it could inform targeted dog vaccination efforts and help mitigate the seasonal surge in rabies cases.

Sri Lanka is an island country located in the Indian Ocean between North latitude 5º 55'– 9º 51' and East longitude 79º 42' – 81º53'. The United Nations estimated the human population in Sri Lanka to be 21.5 million in 2021 (United Nations Population Fund, 2022). Sri Lanka has a tropical climate. Based on rainfall and altitude above sea level, the country can be divided into three climatic zones: the 'dry' zone, the 'wet' zone, and the 'intermediate' zone (Punyawardena, 2008). The dry zone extends northward and eastward from the central highlands. It covers two thirds of the country's land area and receives a total yearly rainfall of between 900–1,750 mm. The wet zone covers the south-western region, including the central hill country and receives a total yearly rainfall >2,500–5,000 mm. The intermediate zone receives a total yearly rainfall of 1,750–2,500 mm and is located between the dry zone and the wet zone (Punyawardena, 2020; Nisansala *et al.*, 2020). The rainfall pattern is influenced by the monsoon winds of the Indian Ocean and the Bay of Bengal, resulting in four seasons, namely First Inter-Monsoon (FIM), South-West Monsoon (SWM), Second Inter-Monsoon (SIM) and North East Monsoon (NEM) (Table 1).

Table 1. Monsoons and climate zones of Sri Lanka (as described in Punyawardena, 2008).

Season	**Period**	**Zonal difference in wet and dry seasons by monthly average rainfall (mm);** Wet (≥100mm/month) and Dry (<100mm/month)		
		Wet zone	**Intermediate zone**	**Dry zone**
First Inter-Monsoon (FIM)	March to April	Mid-March to May (highest rainfall in May)	April to May	Mid-March to Early May (highest rainfall in April)
South-West Monsoon (SWM)	May to September	May to September (lowest rainfall in July and August)	No SWM	No SWM
Second Inter-Monsoon (SIM)	October to November	October to November	September to November	Mid-October to November
North East Monsoon (NEM)	December to February	No NEM	Late November to December (highest rainfall in December, dwindle effectiveness in January)	Late November to December (highest rainfall in December, dwindle effectiveness in January)
Dry months (months receiving <100 mm monthly rainfall)		January to February	January to March June to August	January to March May to September

The objective of this study was to investigate and test the hypothesis of a positive association between rainfall patterns and reported rabies cases in both humans and animals in each of the three climate zones in Sri Lanka. We postulate that if there is such a spatiotemporal association, the evidence might suggest ways of improving the timing of dog vaccination and population control programmes in Sri Lanka.

MATERIALS AND METHODS

Data collection

Data on the number of human and dog rabies-related deaths (rabies cases) per district and by month for the period 2004-2021 were obtained from the Medical Research Institute (MRI) of Sri Lanka, the national reference centre for rabies. Rabies diagnoses had been made using the direct fluorescent antibody test (DFAT), the gold standard test (https://www.mri.gov.lk/units/rabies-vaccine-qc/). Data were only available at the granularity of districts. The current rabies surveillance system in Sri Lanka is based on passive reporting and recording of both clinically and laboratory confirmed human and animal rabies cases. Suspected human deaths are clinically confirmed by sending brain tissue samples obtained during post-mortem examinations to Judicial Medical Officers (forensic pathologists). For animal rabies surveillance, veterinarians submit the head of any suspected rabies case to the Medical Research Institute, Faculty of Veterinary Medicine and Animal Science, University of Peradeniya and Karapitiya Teaching Hospital for diagnostic testing. Additionally, members of the general public are informed via awareness campaigns to submit the head of the dog to above mentioned institutes if the animal is suspected of having clinical signs of rabies including frothy salivation, abnormal behaviour, and aggression. These voluntary submissions by the general public are tested for rabies. Submissions to MRI that were recorded as owned domestic and free roaming dogs, which were DFAT positive were used in this study.

For this study, dates and locations of all confirmed rabies incidents in both humans and dogs were retrieved and summarised by district and by month. Data relating to the area (km^2) and human population of each district were obtained from the Census and Statistics data published in 2012 (Department of Census and Statistics, 2012). In Sri Lanka, the average yearly rate of human population increase ranged from -2.7% to 1.09% for the period 2004 to 2021 (https://www.macrotrends.net/countries/LKA/sri-lanka/population). While the country's population grew at a relatively slow pace, the death rate ranged from 6 deaths per 1000 people to 8.25 deaths per 1000 people for the same period (https://www.macrotrends.net/global-metrics/countries/LKA/sri-lanka/death-rate). People dwelling in 25 districts span over 65,000km2 of total land area, and the fact that individual districts are smaller in land size justifies the assumption that district data does not deviate from national-level trends.

Based on that data, it was considered reasonable to assume that the human population in each of the districts had not changed to such an extent during the 18-year study period as to have introduced undue bias. The human population densities for the districts were calculated by dividing the human population size in each district in 2012 by the respective land area in square kilometres for the human population density maps. Monthly rainfall data by district from 2004 through 2021 were obtained from the Department of Meteorology, Colombo, Sri Lanka (http://www.meteo.gov.lk/index.php?lang=en). For the descriptive analysis, both monthly rainfall data and rabies case counts were summed up for each climatic year, which in Sri Lanka begins in March and ends in February of the following calendar year.

Data Analysis:

Both the dog and human rabies case counts were subjected to descriptive (number of cases by district and by month) and inferential statistical analyses. The geographical information system software ArcGIS version 10.3 (ESRI, Redlands, USA) was used to map the spatial distribution of dog and human rabies case counts by district. The software GeoDa version 1.12.1.161 (Anselin *et al.,* 2006) was used to calculate Moran's I as a global statistic of spatial autocorrelation based on the queen contiguity spatial weights matrix (Moran, 1950). The statistical significance of the global Moran's I (index) was assessed using Monte Carlo randomisation based on 999 permutations. Interpretation of the test was that a statistically significant p-value ($p < 0.05$) indicates the presence of spatial clustering. Spatio-temporal clustering of dog rabies cases and human rabies cases at the granular level of districts was performed as per prospective Space-Time permutation Scan Statistics (Kulldorff and Nagarwalla, 1995) using SATScan v 10.1 software (http://www.satscan.org) at 50% maximum spatial and temporal cluster size. As these two analyses target testing for spatial and spatio-temporal dependency of the adjacent areas, statistically significant Moran's I indices and Space-time clusters indicate that neighbouring districts tend to have similar rabies case counts (Kuldorff, 1999). The SaTScan parameters used were: data type case-only, and the measure of effects observed/expected ratio, $p<0.05$.

The monthly temporal patterns of dog rabies cases, human rabies cases, and average rainfall over the study period were compared across the climatic zones. Because the data were not normally distributed, the Kruskal–Wallis H test was applied to assess differences in monthly dog and human rabies counts among the climatic zones. Post-hoc pairwise comparisons were subsequently conducted to determine which specific zones differed from one another.

In addition, the Mann–Whitney U test was used to examine differences in dog and human rabies occurrence between wet and dry months within each climatic zone. All statistical analyses were performed using SPSS Version 20.

RESULTS

Descriptive analysis of dog and human rabies case numbers

Across Sri Lanka, a total of 502 human and 9,555 dog rabies cases were reported from 2004 through 2021. An average of 28 human rabies cases (Minimum 19; Maximum 44; Standard Deviation 6) and an average of 531 dog rabies cases per year (Minimum 380; Maximum 696; Standard Deviation 105) were shown over the period. The rabies case count distribution by district and climatic zone is shown in Table 2 and Figures 1A and 1B.

Table 2. Total number of dog and human rabies cases from 2004 to 2021, and human population density (persons/km^2) in 2012, stratified by district and climatic zone (H=Human, D=Dog).

Climatic Zone	District	Species	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average	Human populatio
Wet Zone	Gampaha	D	120	106	198	156	200	209	210	161	137	136	132	101	116	112	130	101	81	114	140	1719
		H	1	1	0	0	2	3	2	4	2	2	5	0	0	4	3	1	2	6	2	
	Colombo	D	244	184	245	201	148	184	171	128	115	135	121	91	52	31	19	31	48	180	129	3438
		H	3	4	5	4	3	9	5	2	4	1	1	7	3	1	2	1	3	3	3	
	Kalutara	D	51	32	26	62	67	66	42	46	84	107	51	51	36	21	16	15	39	61	49	775
		H	4	2	2	3	2	3	1	0	2	0	1	2	4	1	0	2	3	2	2	
	Galle	D	21	64	91	108	107	75	26	22	43	62	22	30	19	44	42	35	46	60	51	658
		H	7	1	6	2	4	5	6	4	1	2	1	0	0	1	2	3	3	1	3	
	Matara	D	6	11	16	3	0	1	2	0	33	28	20	15	14	24	8	8	12	6	12	641
		H	6	0	2	3	0	1	1	1	0	2	0	0	0	0	0	1	1	0	1	
	Kegalle	D	5	4	20	13	13	8	11	13	21	7	12	14	12	12	12	19	6	8	12	499
		H	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	
	Kandy	D	2	2	7	5	1	3	1	4	1	1	1	1	2	1	0	4	1	1	2	717
		H	0	0	2	2	3	1	1	1	0	0	1	0	0	3	3	2	0	0	1	
	Nuwara Eliya	D	1	1	1	2	1	2	0	0	3	0	2	2	0	0	1	0	0	1	1	417
		H	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
	Ratnapura	D	13	19	36	17	12	27	12	23	30	18	39	19	16	21	44	52	33	13	25	336
		H	0	2	1	2	0	0	2	2	3	1	1	0	0	0	2	3	1	3	1	
Intermediate Zone	Matale	D	0	2	5	1	1	9	4	5	4	11	10	2	0	1	3	0	1	1	3	248
		H	0	0	1	1	0	1	1	0	2	0	0	0	1	0	0	1	1	1	1	
	Kurunegala	D	5	5	10	9	14	17	9	16	21	27	47	41	48	31	32	26	17	4	21	350
		H	1	0	0	8	7	4	2	2	2	1	1	3	4	4	4	5	5	2	3	
	Badulla	D	2	2	14	7	10	9	9	12	9	2	4	3	8	2	0	3	2	3	6	288
		H	0	3	4	2	0	0	0	0	1	0	0	4	1	1	0	0	0	0	1	

Dry Zone																									
Monaragala		**Hambanthota**		**Kilinochchi**		**Puttalam**		**Ampara**		**Batticaloa**		**Trincomalee**		**Polonnaruwa**		**Anuradhapura**		**Vavuniya**		**Mannar**		**Mullaitivu**		**Jaffna**	
H	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D
1	0	0	2	0	0	0	8	0	0	0	1	0	1	0	2	0	3	0	0	0	0	0	0	0	0
0	1	1	5	0	0	1	6	0	1	0	0	2	0	0	2	0	1	1	0	0	0	0	0	0	0
0	2	0	2	0	0	2	15	0	0	0	0	0	3	0	2	4	2	0	0	1	0	0	0	0	1
1	2	0	4	0	0	0	28	0	1	0	1	0	1	0	2	3	2	1	1	0	0	0	0	0	1
1	2	0	2	0	0	2	41	0	4	1	0	1	1	1	1	2	3	1	0	0	0	0	0	0	1
4	7	0	3	0	0	3	45	0	1	3	1	1	0	0	0	5	3	0	0	0	1	0	0	0	2
2	10	1	2	1	0	1	40	0	4	6	1	0	1	0	0	4	3	1	0	0	0	0	0	1	0
2	5	2	2	1	0	3	36	1	1	5	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0
2	5	0	21	0	1	3	44	3	5	3	2	0	1	1	8	2	11	0	0	0	1	0	0	1	0
3	11	0	18	1	0	1	72	0	4	3	2	1	0	2	4	3	10	2	0	0	1	0	0	2	0
1	42	0	27	0	0	2	62	0	5	2	1	0	1	0	2	1	2	0	0	0	0	1	2	1	3
0	22	0	8	1	0	4	58	0	0	1	2	0	1	0	1	2	4	0	3	0	0	0	0	0	2
1	27	0	8	0	0	1	35	0	2	0	8	2	3	0	1	0	3	0	1	0	1	0	0	3	0
2	8	2	31	0	2	0	49	0	2	0	6	0	1	1	0	2	3	0	1	0	0	0	0	1	2
1	12	0	9	1	0	0	37	0	1	3	2	0	2	1	1	2	5	1	2	0	0	0	1	0	1
1	41	1	20	0	0	0	30	0	0	1	5	1	8	1	20	1	1	0	1	0	0	0	1	1	3
0	55	2	17	0	0	0	30	1	0	1	7	0	12	1	8	2	0	0	1	0	0	1	4	4	3
0	48	0	15	1	0	0	25	0	1	0	3	0	14	1	17	1	2	0	0	0	0	0	0	4	4
1	17	1	11	1	1	1	37	1	2	2	2	1	3	1	4	2	3	1	1	1	1	1	1	1	1
	82		240		94		265		154		223		150		132		129		92		53		38		629

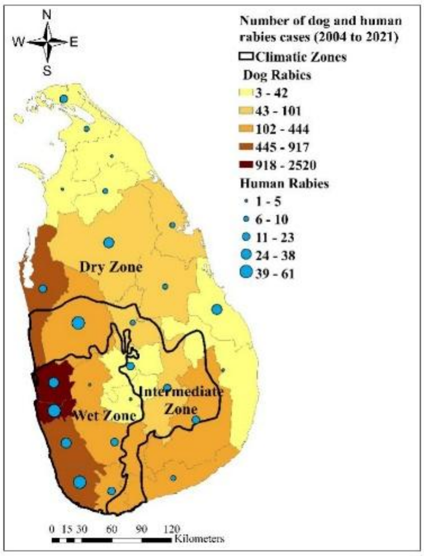

Figure 1A. Spatial distribution of district-level total dog and human rabies case counts in Sri Lanka by climatic zone from 2004 through 2021.

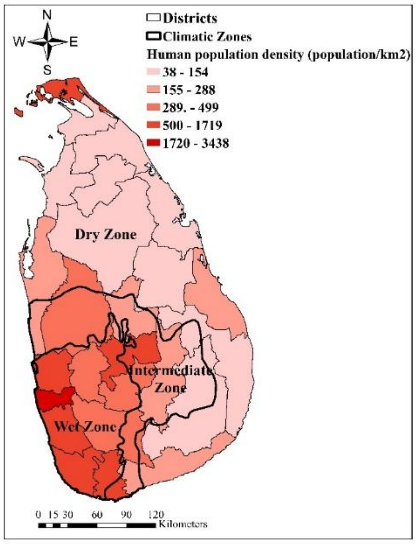

Figure 1B. Spatial distribution of human population density (population/km^2) by districts in Sri Lanka based on the human population data in 2012.

Spatial analysis of dog rabies case count patterns

Global Moran's I indicated a statistically significant positive spatial autocorrelation in dog rabies case counts across the 25 districts of Sri Lanka for the study period ($I = 0.40$, $p = 0.002$, $z = 4.08$). A similar pattern was observed for human rabies, which also showed significant spatial clustering ($I = 0.22$, $p = 0.02$, $z = 2.25$).

The Kruskal–Wallis H test demonstrated significant differences in dog rabies cases among the climatic zones ($H = 1110.24$, $n = 9555$, $p < 0.001$). Human rabies occurrences also differed significantly across zones ($H = 60.6$, $n = 502$, $p < 0.001$). Summary case counts by climatic zone are presented in Table 2. Post-hoc comparisons showed that both dog and human rabies occurrences in the Wet Zone were significantly higher ($p < 0.001$) than in the Dry and Intermediate Zones. Dog rabies counts were 7,554 in the Wet Zone, 1,461 in the Dry Zone, and 540 in the Intermediate Zone, while human rabies counts were 247, 174, and 81, respectively.

Pairwise comparisons indicated that dog rabies differed significantly among all three climatic zones ($p < 0.001$). For human rabies, significant differences were found only between the Dry and Wet Zones ($p < 0.001$) and between the Dry and Intermediate Zones ($p < 0.001$).

Space–time (SP-T) cluster analysis revealed that, although dog rabies is endemic in Sri Lanka, both dog and human rabies clusters predominantly occurred in the Wet Zone, reflecting similar spatial–temporal patterns of disease occurrence (Figures 2A and 2B; Tables 3 and 4). Dog rabies clusters were consistently detected in the Wet Zone with

observed-to-expected ratios greater than 1.0 from 2004 to 2015 (Clusters 1–5). In contrast, human rabies clusters were fewer and limited to 2004–2006, with observed-to-expected ratios greater than 3.0 (Clusters 1 and 2). A more recent dog rabies cluster detected in the Central and Northeastern Provinces from 2014 to 2020 (Cluster 6), covering both Dry and Intermediate Zones, did not coincide with an increase in human rabies cases (Tables 3 and 4).

Clusters were detected using the space-time permutation model of the spatial scan statistics with 50% spatial and time windowsmodel of the spatial scan statistics with 50% spatial and time windows

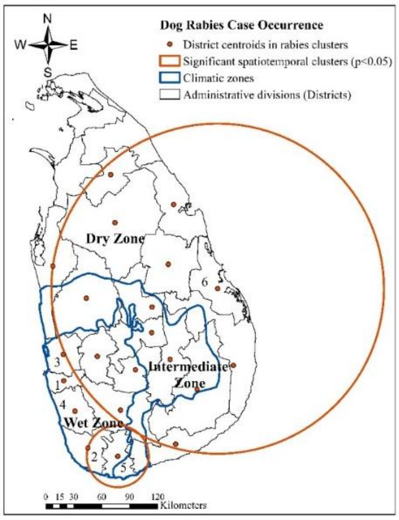

Figure 2A. Spatiotemporal clustering of dog rabies cases in Sri Lanka

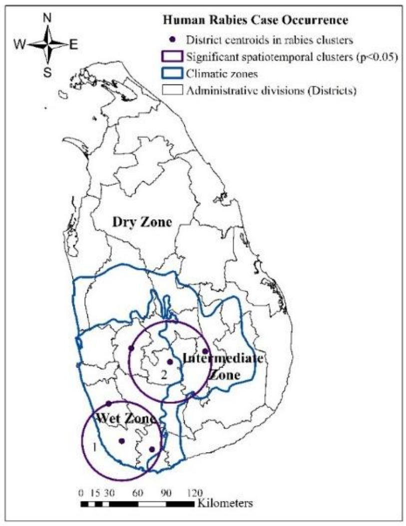

Figure 2B. Spatiotemporal clustering of human rabies cases in Sri Lanka. Clusters were detected using the space-time permutation

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Table 3.
Statistically significant spatiotemporal clusters of dog rabies cases (at p-value <0.05).

Cluster number	Districts included in the cluster	Time frame	Observed	Expected	Observed/ Expected
1	Colombo	2004/1/1 to 2007/12/31	874	550.14	1.59
2	Matara, Galle	2005/1/1 to 2008/12/31	400	282.32	1.42
3	Gampaha	2008/1/1 to 2011/12/31	780	616.35	1.27
4	Kalutara	2012/1/1 to 2013/12/31	191	114.76	1.66
5	Matara	2012/1/1 to 2015/12/31	96	50.59	1.9
6	Batticaloa, Polonnaruwa, Matale, Ampara, Kandy, Badulla, Trincomalee, Monaragala, Nuwara Eliya, Anuradhapura, Kurunegala, Kegalle, Rathnapura, Vavuniya, Hambanthota, Puttalam	2014/1/1 to 2020/12/31	1364	873.33	1.56

Table 4. Statistically significant spatiotemporal clusters of human rabies cases (at p-value <0.05).

Cluster number	Districts included in the cluster	Time frame	Observed	Expected	Observed/Expected
1	Galle, Matara, Kalutara	2004/1/1 to 2004/12/31	17	4.83	3.52
2	Nuwara Eliya, Badulla, Kegalle	2005/1/1 to 2006/12/31	10	2.13	4.69

Temporal analysis of dog and human rabies case count patterns

The monthly patterns of dog and human rabies counts together with average monthly rainfall across climatic years (March to February) are shown in Figure 3. We observed a distinct bimodal pattern of average monthly rainfall across the zones, with the wet zone's pattern being particularly prominent. The dog rabies cases time series seemed to have an inverse relationship between dog rabies cases and rainfall pattern, especially the dry months having more reported cases (Figure 3 and Table 5).

Figure 3. Bar chart of the total number of monthly dog and human rabies cases and average monthly rainfall in the three climate zones of Sri Lanka from 2004 through 2021. Monthly data show a bimodal distribution of rainfall, which is followed by high dog and human rabies occurrence in dry months.

Table 5. Dog and human rabies cases in the dry and wet months in different climate zones (The Mann-Whitny U test was used to evaluate the differences between wet and dry months for dog rabies occurrence and human rabies occurrence in climatic zones).

Climate Zones	Dog Rabies	Human Rabies
Wet Zone	Dry months (n=4237, 56.1%) and Wet months (n=3317, 43.9%) *U*=424276, z=3.979, p=<0.001	Dry months (n=121, 49%) and Wet months (n=126, 51%) *U*=471263, z=0.164, p=0.87
Dry Zone	Dry months (n=813, 55.6%) and Wet months (n=648, 44.4%) *U*=926689, z=2.060, p=0.039	Dry months (n=100, 57.5%) and Wet months (n=74, 42.5%) *U*=954565, z=0.488, p=0.625
Intermediate Zone	Dry months (n=285, 52.8%) and Wet months (n=255, 47.2%) *U*=45945, z=2.664, p=0.008	Dry months (n=37, 45.7%) and Wet months (n=44, 54.3%) *U*=50427, z=0.836, p=0.403

Dog rabies cases tend to surge during dry months significantly in comparison with wet months in all three climatic zones. This pattern of temporal causality was not statistically significant for either the Intermediate or Wet Zones with respective to human rabies cases except for Dry zone (Table 5, Figure 4).

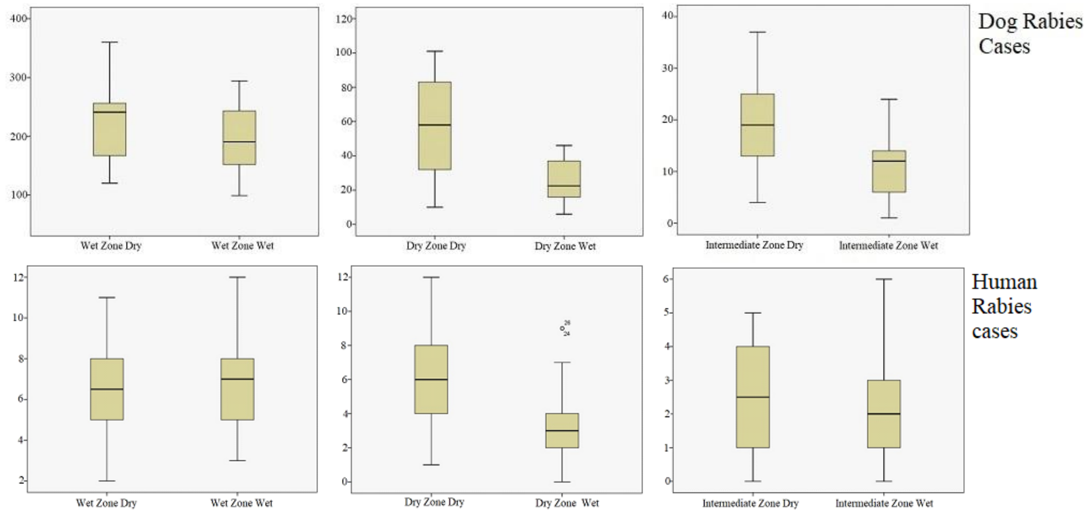

Figure 4. Distribution of dog rabies and human rabies cases by climatic zone (wet, dry, intermediate) and season (dry, wet) between 2004 and 2021

DISCUSSION

This study emphasises the importance of accounting for climatic zones when analysing rabies patterns in Sri Lanka between 2004 and 2021. Spatial and temporal analyses revealed distinctly different occurrences of rabies across the Wet, Dry, and Intermediate Zones, with a notable increase in dog rabies cases during the dry season in all three zones, as shown by the Mann-Whitney U test. Although causation cannot be inferred, these associations support the hypothesis that rainfall can serve as a proxy for predicting fluctuations in dog rabies incidence. The findings suggest a potential “monsoon association,” particularly in the Wet Zone. Differences in dog rabies occurrence between climatic zones during dry and wet months were statistically significant, whereas no such variation was found for human rabies based on the Kruskal–Wallis H and Mann–Whitney U tests. The Wet Zone also recorded the highest number of spaces–time clusters for both dog and human rabies.

While further data on dog population dynamics are needed to confirm the observed rainfall and rabies association, these findings provide a valuable framework for identifying high risk periods and planning targeted biannual dog vaccination campaigns. In resource-limited settings such as Sri Lanka, understanding climatic influences on dog reproductive cycles, such as rainfall induced mating and population fluctuations can strengthen rabies control strategies and improve public awareness (Brookes *et al*., 2016; Gebru *et al*., 2019).
Previous research has reported seasonal reproductive patterns in dogs linked to monsoons,

with mating peaks typically occurring in October–November and April (Pal, 2001; Chawla and Reece, 2002; Pal, 2011). Increased humidity during monsoon months enhances pheromone signaling, which can stimulate reproductive activity (Sen and Bhadra, 2015). Consequently, Sri Lankan dogs likely follow a biannual breeding cycle that aligns with the bimodal rainfall pattern, resulting in higher pup populations during the dry months (January–March and August). Monsoon conditions may also influence shelter-seeking behavior and animal interactions, thereby facilitating disease transmission (Cunha Silva *et al.,* 2022).

The observed association between monsoon patterns and rabies incidence has not been previously documented in Sri Lanka. Elevated numbers of dog rabies cases were recorded during months receiving less than 200 mm rainfall in the Wet Zone and less than 100 mm in the Dry and Intermediate Zones, particularly in January, February, March, and August. These dry periods may increase dog mobility in search of food and water, heightening opportunities for disease transmission. A similar seasonal rise in dog rabies cases has been observed in India, notably during March and August (Brookes *et al.,* 2016).

Consistent with previous reports (Karunanayake *et al.,* 2014), rabies hotspots for both dogs and humans were concentrated in the Wet Zone, especially in Colombo, Gampaha, Kalutara and Galle districts. The higher incidence in these areas may be attributed to greater human and animal population densities, increased passive surveillance, and post-tsunami displacement that enhanced human–animal interactions. Positive correlations between human and dog rabies cases, as well as between population density and rabies incidence, have been observed in other regions, including Tunisia (Bouslama *et al*., 2020) and South Africa (Koeppel *et al.,* 2021).

Several limitations should be acknowledged. Passive surveillance likely led to underreporting due to limited transport facilities and public awareness in rural areas. The absence of district level dog population data also restricted analysis, as dog density is a major determinant of rabies transmission (Morters *et al*., 2013). Future studies incorporating real-time dog demographic data would improve planning, for example, scheduling spay-neuter programs before the rainy seasons and vaccinating pups soon after, when maternal antibody protection wanes.

High dog turnover rates, exclusion of puppies from vaccination programs, and unrestricted breeding complicate maintenance of adequate herd immunity (Coleman and Dye, 1996; Hampson *et al*., 2009; Morters *et al*., 2015). Understanding reproductive seasonality is therefore critical for effective population control (Brill *et al*., 2022; Thahaby *et al*., 2021). Sustainable rabies prevention requires an integrated approach that combines mass sterilisation, regular vaccination, and monitoring of dog activity during monsoon periods.

Recognising the influence of climatic and environmental factors alongside human and animal variables align with the One Health approach to rabies prevention (Hamta *et al*., 2021; Rupprecht *et al*., 2020). Seasonality in rabies occurrence has also been reported elsewhere, such as in China, where human cases peak during summer (Zhang *et al*., 2012). The indirect but consistent rainfall and rabies association, particularly in the Wet Zone, should be integrated into risk-based vaccination strategies, e.g., vaccinating adult dogs before the rainy season and targeting pups afterwards. Further studies should focus on the temporal dynamics of dog populations and employ detailed spatiotemporal analyses of outbreaks and vaccination programs to refine rabies control efforts (Karunanayake *et al*., 2014; Kanankege *et al.,* 2022).

CONCLUSIONS

The observed potential association between monsoons and dog rabies cases reported in Sri Lanka and its indirect nature implies an important finding that sets a foundation for further investigation. Empirical data on dog population, dog ecology, and the rainfall association with dog turnover are needed to further improve the understanding of rabies epidemiology. This study highlights the value of using rainfall as a proxy for determining high risk periods for risk-based vaccination programmes to better plan pre-rainy season spay-neuter activities and post-rainy season targeted vaccination campaigns of <1 year old pups.

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