

Research Article

An analysis of mixed linear model, lagged rainfall effects on gastrointestinal parasite intensity in Chacma baboons, Filabusi, Zimbabwe

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Abstract The spread of zoonotic diseases jeopardizes public health and wildlife conservation. Environmental, edaphic, and biological factors influence parasite intensity, thereby impacting zoonotic disease transmission. This study investigated the impact of rainfall, year, parasite type, and troops on the intensity of gastrointestinal parasites in Chacma baboons at Epoch Mine Campus, Gwanda State University, located in Filabusi, Insiza District. Data were collected in 2023 and 2024. A number of linear mixed-effects models were constructed to evaluate the factors influencing gastrointestinal parasite intensity in baboons. The analysis revealed two notable interaction effects regarding parasite intensity. The interaction between year and parasite type showed a substantial increase in parasite intensity in 2023 and 2024 (Estimate = 169.80, $p < 0.001$), even after controlling for rainfall factors. In contrast, lagged models showed no significant improvement, with a difference in the Akaike Information Criterion (ΔAIC) of less than 0.15. It is concluded that rainfall, year, and parasite type may influence the intensity of gastrointestinal parasites, but rainfall effects vary across parasites.

Keywords Chacma baboons; gastrointestinal parasites; linear mixed-effects model; rainfall variability; zoonotic disease

Introduction

Zoonotic infectious diseases affect humans, domestic and wild animals, with many transmitted across species (Cunningham et al., 2017). Public health and wild animal conservation are being threatened by zoonotic emerging and re-emerging diseases (Cibot et al., 2015). Non-human primates (NHPs) serve as hosts for most zoonotic parasites that affect humans, likely due to their genetic proximity to humans (Banda et al., 2024). Although humans and NHPs live interdependently, the detrimental consequences of zoonotic parasite exchange may result from sharing the same environmental niche (Chapman et al., 2005). Due to climate variability, seasonal variations, and habitat overlap shared between NHPs and humans, the spread of zoonotic diseases can be promoted (Borham et al., 2025). Gastrointestinal parasites among Chacma baboons were recently reported in Zimbabwe, with six taxa that were identified (Banda et al., 2024). Habitat loss

and fragmentation are major forces driving parasite prevalence, diversity, and intensity (Hussain et al., 2013).

Cibot et al. (2015) carried out a study in Uganda and reported that gastrointestinal parasites were more prevalent during the rainy season. During the rainy season, the sleeping behaviour of baboons is reported to be altered by the prevalence of predators in sleeping sites and by resource availability, thereby affecting parasite prevalence (Markham et al., 2016). Gastrointestinal parasite prevalence and intensity depend on seasonal changes in microhabitats. Rainfall seasonality significantly affects the risk of gastrointestinal parasite infection in hosts, influencing infection prevalence and intensity (Habig et al., 2021). Rainfall has a significant impact on the dynamics of gastrointestinal parasites in baboons, influencing parasite survival and host behaviour, and consequently host exposure to infection, with implications for public health at the human-wildlife interface (Johnson et al., 2013; Akinyi

et al., 2019). Blersch et al. (2021a), in their study on seasonal effects on gastrointestinal parasite prevalence, richness, and intensity in Vervet monkeys living in a semi-arid Karoo biome in South Africa, reported that gastrointestinal parasites responded differently to rainfall availability. Annual variations in *Protospirura* spp. Egg count was very high in spring, but variations were also observed in weekly precipitation, with higher precipitation associated with lower *Protospirura* spp. egg counts. Seasonal changes, diet, and behaviour exert strong influences on gastrointestinal parasite dynamics in baboons, thereby impacting their susceptibility to infection (Benavides et al., 2012). Benavides et al. (2012) in their study in Central Namibia, observed that higher intensities of some helminths occur during dry seasons due to nutritional stress and exposure to environmentally driven stages of soil-borne parasites. However, some could be favoured by humid wet conditions (Mignatti et al., 2016).

Akinyi et al. (2019) investigated the costs and causes of helminth parasite infection in wild female baboons in Kenya. They utilised a general mixed linear model and found that low rainfall and low temperatures were associated with increased risk of helminth infection. Females had the highest *Trichuris trichiura* egg counts during cool, dry times. Females who lived in low-rainfall areas were likewise more likely to contract *Abbreviata caucasica*, but less likely to contract *Streptopharagus pigmentatus*. Akinyi et al. (2019) further observed that seasonal rainfall fluctuations heavily shaped baboon immunology and behaviour, ultimately resulting in strong temporal variation in parasitic infections. Higher infection rates occurred during the dry season, while *T. trichiura* and other parasites were favoured during the wet season (Akinyi et al., 2019).

Habig et al. (2021) at Cape Town, South Africa, investigated the predictors of helminth parasite infection in female Chacma baboons (*Papio ursinus*). Random-intercept mixed-effects models were used to investigate predictors of specific helminth infections. The researchers concluded that female Chacma baboons showed individual variation in helminth richness and infection intensity, which appeared to be driven by four factors: reproductive state, steroid hormone profiles, rainfall patterns, and co-infection dynamics. Seasonal changes in temperature and rainfall influence host stress and behaviour, making hosts more susceptible to diverse parasite taxa during particular seasons (Akinyi et al., 2019; Habig et al., 2021).

In Southern Africa, Chacma baboons have a bimodal infection peak, with higher gastrointestinal helminth burdens in summer and winter (Zinner et al., 2018). The infection patterns of Chacma baboons in the Cape Peninsula have been reported to be highly seasonally influenced, as heat stress combined with a decline in food quality in the dry season rendered baboons permissive to *Protospirura* spp and *Trichuris* spp, while the cool, wet winter months enhance the survival of *Oesophagostomum* spp. larvae (Terio et al., 2018). Unfavourable conditions for host-bond parasites and infections, as well as possible animal-human pathogen exchange, were driven by climatic variables and host physicality (Borham et al., 2025). Seasonal variations on the Cape Peninsula significantly affected the patterns

of parasitic infection in Chacma baboons (Mignatti et al., 2016). The parasitic loads were lower during the wet season, thereby increasing parasite transmission, as the relatively cool temperatures and wet conditions favoured transmission. A higher parasitic load occurred during the dry season, when baboons were more stressed by the heat, their food was of lower quality, and they spent more time foraging (Pebsworth et al., 2012). The seasonal dynamics of gastrointestinal parasites in baboons in West and Central Africa followed a pattern similar to that observed in Southern Africa. Ecological changes in seasonal rainfall and temperature had substantial effects on parasite community composition and prevalence rates, thereby affecting baboon health and zoonotic transmission potential (Hoffman & O'Riain, 2011, 2012).

Previous research has focused on the prevalence, diversity, and intensity of gastrointestinal parasites influenced by variable climatic conditions across different baboon troop species (Ravasi, 2009; Banda et al., 2024). Research using general and intercept-mixed linear models was conducted to determine the costs and causes of helminth parasite infection and to assess predictors of helminth parasite infection in female baboons (Akinyi et al., 2019; Habig et al., 2019). There is, however, a scarcity of research on assessing rainfall-dependent, parasite-specific, and inter-annual variation in gastrointestinal parasite intensity in Chacma baboon troops, particularly on biologically meaningful interaction effects using generalised linear mixed models in Zimbabwe and beyond. Also, there is limited knowledge on the influence of past monthly rainfall on the intensity of parasite species. This study, therefore, filled a research gap by constructing several general linear mixed models to examine the effects of rainfall, parasite type, and year on gastrointestinal parasite intensity in Chacma baboons. It further estimated parameters from the best-fitting model and investigated the potential effects of delays in monthly rainfall events on subsequent changes in parasite mean intensity. It was hypothesized that rainfall availability significantly affects the intensity of gastrointestinal parasites in Chacma baboons.

Materials and Methods

Study Area

The study was conducted in Filabusi, Insiza district, at the Epoch Mine campus, Gwanda State University (20°26'11.37"S; 29°16'08.64"E) (Figure 1). According to Onema et al. (2006) Epoch Mine is situated between 1420 and 1500 meters above sea level. The Insiza district is one of the seven districts in the Matabeleland South Province, Zimbabwe. The Gwanda district is located to the south, the Zvishavane district to the east, and the Umzingwane district to the west (Pirajno & González-Álvarez, 2013). The district is approximately 106 km southeast of Bulawayo, Zimbabwe. This area experiences severe dry spells throughout the rainy season and sporadic seasonal droughts, with an average annual rainfall of 350 mm (Musara et al., 2021). The district is primarily located in the natural Agro-region IV. Months of June and October

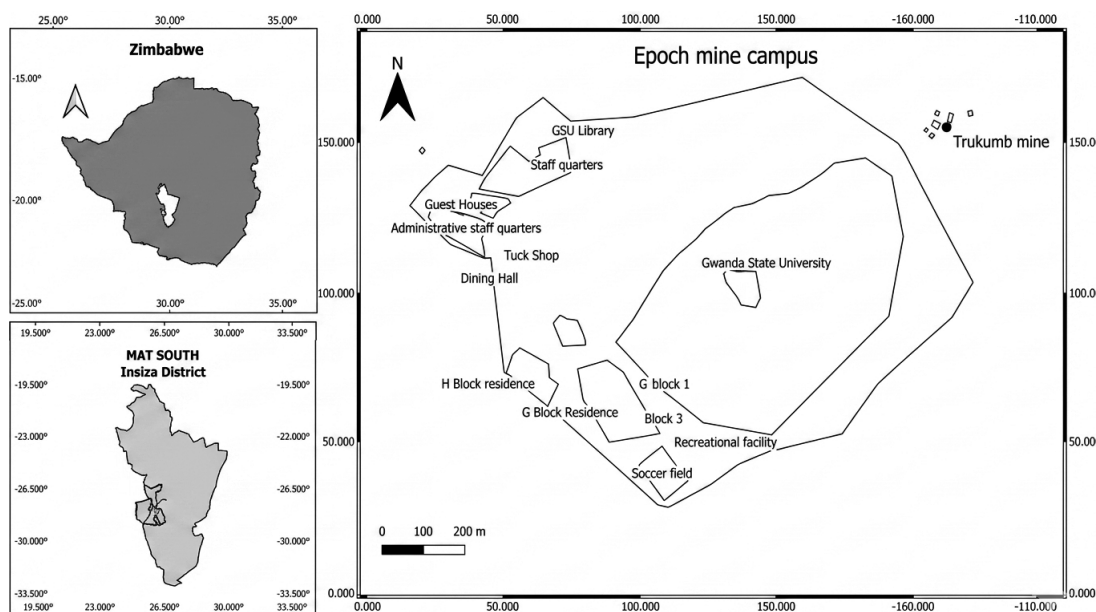


Figure 1. Location of Gwanda State University, Epoch Mine campus, Insiza District, Matabeleland South, Zimbabwe. Adopted from Banda et al., 2024.

have the lowest and highest temperatures, respectively, with a range of 12 °C to 29 °C (Onema et al., 2006).

The study area, once an abandoned mine, was later revitalized and repurposed for the establishment of a tertiary institution. Since the tertiary institution's establishment in 2016, baboons have already established themselves and coexist with other primates, such as Vervet monkeys (*Chlorocebus pygerythrus*). These Chacma baboons spend a substantial amount of time wandering in and out of the campus. On campus, especially in the staff and student quarters, they are observed foraging for food in trash cans and dump sites, harvesting unripe fruits, debarking tree trunks, and defecating anywhere, thus making residents more vulnerable to infections. More details of the study area are provided by Banda et al. (2024).

Data Collection

The method for collecting and processing fecal samples to characterize gastrointestinal parasites used in this study is adapted from Banda et al. (2024). Rainfall data from 2023 to 2024 used in this study were obtained from the Department of Agricultural, Technical, and Extension Services (AGRITEX) in the Insiza District (unpublished data).

Data Analysis

A number of linear mixed-effects models were constructed to evaluate the factors influencing gastrointestinal parasite intensity in baboons. Linear mixed-effects models enabled robust estimation of rainfall effects while controlling for troop-level clustering. Yet, the absence of individual-level tracking means our inferences remain at the population rather than the individual scale. The categorical variable Parasite Type comprising Strongylids, *Entamoeba* spp., Coccidia, *Schistosoma* spp., *Fasciola* spp., and *Subulura*

spp. was included in the linear mixed-effects model using dummy coding with Strongylids as the reference level due to their highest prevalence and established rainfall sensitivity, allowing comparison of all other parasite taxa against this ecologically dominant group. The models increasingly incorporated the fixed effects of mean monthly rainfall, parasite type, and year, along with their interactions. Troop identity was included as a random intercept in all models to account for repeated measures and inherent differences between social groups (Blersch et al., 2021b). Model selection was performed using Akaike's Information Criterion corrected (AICc) for small sample sizes. The basic model structure was:

$$A_{ijpt} = \beta_0 + \beta_1 R_{ij} + \beta_2 Y_j + \beta_3 P_p + \beta_4 (R_{ij} \times Y_j) + \beta_5 (R_{ij} \times P_p) + \beta_6 (Y_j \times P_p) + \beta_7 (R_{ij} \times P_p \times Y_j) + \mu_t + \varepsilon_{ijpt}$$

Parameter Estimates from the Best-Fitting Model

Parameter estimates (Table 1) were derived from the top-ranked linear mixed-effects model selected using Akaike's Information Criterion corrected (AICc) for small sample size. Analyses were conducted in R version 4.2.2 using the lme4 and lmerTest packages. The response variable was mean gastrointestinal parasite intensity. Consistent with standard practice in quantitative parasitology, EPG counts were log (intensity+1), transformed to accommodate the aggregated distribution of parasites among hosts. This approach accounts for the zero-inflation in the data while appropriately scaling the geometric increases in egg output associated with rising parasite burdens, which other transformations cannot.

The final model included a three-way interaction between mean monthly rainfall, year, and parasite type, with troop identity included as a random intercept to account for repeated sampling and social group structure. Model parameters (Table 1) were estimated using

Table 1. Fixed linear model parameter description.

Variable	Description	Dimensions
A_{ijpt}	Mean monthly parasite intensity measured for sample i in year j , for parasite type p , in troop t	EPG
β_0	Fixed intercept of the overall Chacma baboons population parasite intensity	EPG
β_1	Fixed effect model coefficient of mean monthly rainfall	EPG per mm
β_2	Fixed effect model coefficient associated with year	EPG deviation from 2023
β_3	Fixed effect model coefficient associated with parasite type	EPG deviation from Strongylid
β_4	Fixed effect model coefficient of the interaction of mean monthly rainfall and year	EPG per mm deviation from 2023
β_5	Fixed effect model coefficient of the interaction of mean monthly rainfall and parasite type	EPG per mm deviation from Strongylid
β_6	Fixed effect model coefficient associated with the interaction of year and parasite type	EPG deviation from Strongylid in 2023
β_7	Fixed effect model coefficient of the interaction of mean monthly rainfall, year, and parasite type	EPG per mm deviation from Strongylid in 2023
R_{ij}	Mean monthly rainfall associated with sample i in year j .	mm
Y_j	Categorical year effect (2023 vs. 2024, fixed effect)	EPG deviation from 2023
P_p	Indicator (or categorical coding) for parasite type p	EPG deviation from Strongylid
μ_t	Random intercept for troop t , capturing troop-specific deviations assumed to follow a normal distribution with mean 0, variance $\sigma^2 N(0, \delta_\mu^2)$	EPG
ε_{ijpt}	Residual error assumed to follow a normal distribution with mean 0, variance σ^2	EPG

restricted maximum likelihood (REML). Degrees of freedom and p-values for fixed effects were obtained using Satterthwaite's approximation, with statistical significance assessed at $\alpha = 0.05$. Model assumptions were evaluated using residual diagnostics and Q-Q plots. Variance partitioning was used to quantify the contribution of troop-level effects to overall heterogeneity in parasite intensity. Parameter estimates from the final model were interpreted to assess rainfall-dependent, parasite-specific, and inter-annual variation in gastrointestinal parasite infections, with emphasis on biologically meaningful interaction effects.

Lagged Monthly Rainfall Analysis

To investigate potential delays between monthly rainfall events and subsequent changes in parasite mean intensity, we compared models that incorporated rainfall from the previous month (1-month lag) and two months prior (2-month lag) against the top contemporary model (Model m5 in Table 1, which uses current-month rainfall). All models included the critical year-parasite type interaction term identified in our primary analysis and the random intercept for troop t .

Ethics Statement

Ethical approval was sought and obtained from Gwanda State University for this study. A non-invasive method was used to collect fecal samples from baboons without them being disturbed or handled. No animals were harmed during sample collection.

Results

Mixed-Effects Model Analysis

The candidate models were ranked from best to worst fit, based on AICc values (Table 2). The best-supported model

has the lowest AICc score. The AICc weight indicates the relative probability that a given model is the best among the set. Model m5, which included the three-way interaction between mean monthly rainfall, year, and parasite type, was overwhelmingly supported as the best approximating model for the data (AICc weight = 1.000). The considerable Δ AICc values (all > 26) for all competing models m1-m4 indicate that these models had essentially no support relative to the full model.

Significance was determined at $\alpha = 0.05$; hence, the model assumptions were validated using residual diagnostics and Q-Q plots (Fig. 2). Three extreme outliers were excluded from analysis due to potential fecal sample contamination. The troop random intercepts fall approximately along the diagonal in the Q-Q plot, suggesting that troop-level deviations from the mean parasite intensity are random and normally distributed, thereby validating the LMM assumption (Chapman et al., 2005).

Parameter Estimates from the Best-Fitting Model

Parameter estimates from the best-supported model (m5: mean_monthly_rainfall_mm, year, parasite_type + (random intercept for troop)) are presented in Table 3. The model explained substantial heterogeneity in parasite intensity, with the random effect of Troop accounting for 8.2% of the residual variance (Variance = 57.52, SD = 7.58). Significant fixed effect parameter estimates from the top-ranked model (m5) statistically significant terms and their constituent main effects are shown for clarity. The full model output is provided in the supplementary R output.

The model revealed two highly significant interaction effects, both specific to Strongylid: the year-by-parasite-type interaction term (Year 2024: parasite_type_Strongylid). The extremely large and positive coefficient (Estimate = 169.80, $p < 0.001$) indicates that the intensity of Strongylid parasites was significantly higher in 2024 than in 2023, after accounting for monthly rainfall. This represents a

Table 2. Linear mixed effects models.

Model	Fixed Effects Structure	K*	logLik	AICc	Δ AICc	AICc Weight
m5	Rainfall $\times$ Year $\times$ Parasite_Type	30	-562.91	1205.4	0.00	~1.00
m2	Rainfall + Year + Parasite_Type	11	-603.97	1232.3	26.85	~0.00
m3	Rainfall $\times$ Year + Parasite_Type	12	-604.36	1235.5	30.08	~0.00
m1	Rainfall + Parasite_Type	10	-608.52	1238.9	33.54	~0.00
m4	Rainfall $\times$ Parasite_Type + Year	17	-614.68	1269.0	63.62	~0.00

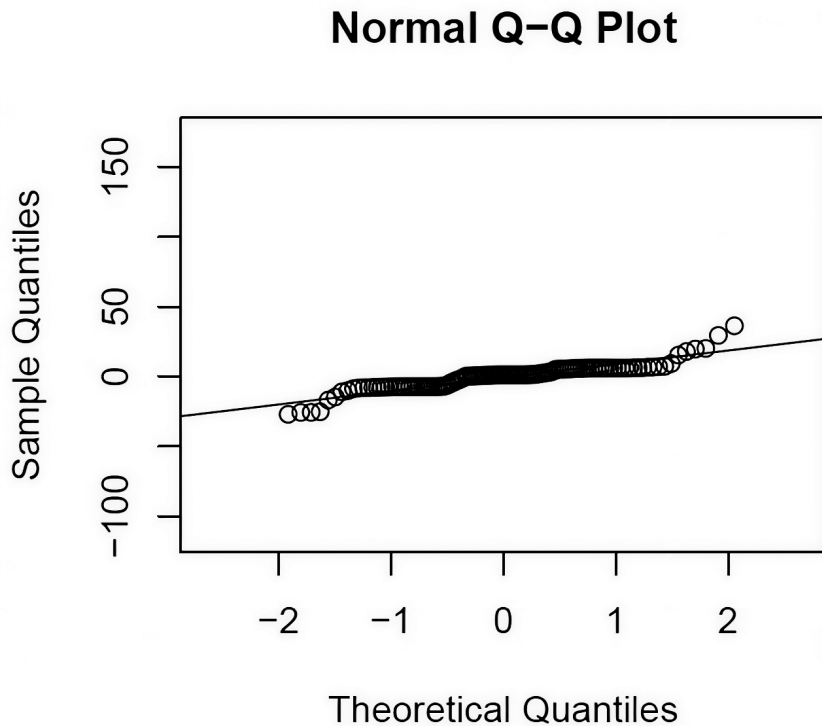


Figure 2. Normal Q-Q plot of sample Quantiles and Theoretical Quantiles.

Table 3. Parameter Estimates from the Best-Fitting Model.

Parameter	Estimate	Std. Error	df	t value	p value
β_6	169.80	22.89	96.0	7.419	< 0.001
β_7	-0.604	0.133	96.0	-4.530	< 0.001
β_3	27.48	15.71	96.0	1.750	0.083

massive main effect of rainfall on this specific parasite group, suggesting that an unmeasured, year-specific ecological driver may have come into play, such as temperature, host density, or immune suppression, which led to a drastic increase in Strongylids in 2024.

Lagged Monthly Rainfall Analysis

There was no significant improvement ($p < 0.15$) from lagged monthly rainfall Models. Based on their extremely comparable AIC values. The models employing lagged rainfall predictors (M_{t-1} ; M_{t-2}) and the model utilising contemporaneous rainfall (M_t) performed almost identically (Table 4). This suggests that delayed rainfall factors do not significantly outperform contemporaneous rainfall in explaining parasite intensity for this system and dataset. There was no combined impact of several lags compared to

the simpler models; the model that included all three rainfall measurements at once (M_t ; $t-1$; $t-2$) fared much worse (Δ AIC > 26). This implies that the lagged variables lack distinctive explanatory power and are likely collinear with the current monthly rainfall measure.

The model comparison reveals that the influence of monthly rainfall on parasite intensity is best represented by models that account for both current and past rainfall. While Mt-2 (AIC = 309.74) is mathematically the top-ranked model, the extremely small AIC differences among the top three models (Δ AIC ≤ 0.15) preclude strong claims about the superiority of any specific lag structure. In particular, there was no strong evidence favouring a specific rainfall lag as the dominant predictor of parasite intensity. The three best models collectively demonstrate that rainfall significantly influences gastrointestinal parasite intensity, but the precise timing of this effect, whether immediate or delayed, could be resolved. Their lower AIC values than the present rainfall model (M_t , AIC = 309.89) show that the parasites are not only influenced by the current rain but also by the moisture conditions of the previous month, which is in line with delayed growth and extinction of the free-living parasite stages due to their being in the soil. The combined model (M_t ; $t-1$; $t-2$), on the other hand, did not

Table 4. Model comparison for lagged rainfall effects on log-transformed parasite intensity.

Model	Fixed Effects Structure	df	AIC
M_{t-2}	$\text{Rainfall}_{t-2} + \text{Year} \times \text{Parasite_Type}$	17	309.74
M_{t-1}	$\text{Rainfall}_{t-1} + \text{Year} \times \text{Parasite_Type}$	17	309.85
M_t	$\text{Rainfall}_t + \text{Year} \times \text{Parasite_Type}$	17	309.89
$M_{t,t-1,t-2}$	$\text{Rainfall}_t + \text{Rainfall}_{t-1} + \text{Rainfall}_{t-2} + \text{Year} \times \text{Parasite_Type}$	19	335.85

perform well at all (AIC = 335.85), which indicates that collinearity and over-parameterization were the issues.

Discussion

Better performance of Model 5's better performance suggest that there is variation in the link between parasite intensity and mean monthly rainfall, year, and parasite type across the system. Rather, the impact of rainfall depends on a complicated interplay between the parasite taxon and the yearly environmental setting. These simpler structures are insufficient to explain the observed patterns, as evidenced by the poor fit of models that assumed uniform rainfall impacts across parasite kinds (Models 2–4) or that neglected the yearly context of these connections (Model 1). Thus, the parameters of Model 5 serve as the foundation for any further inference.

After testing 5 models, the selection shows that the candidate model with the highest complexity provided the best fit to the data. The model that was most strongly supported (Model 5) in particular contained a three-way interaction among mean rainfall, year, and parasite type, as well as a random troop effect. This model illustrates a substantially larger amount of variation in parasite intensity, with the random intercept for troop accounting for only eight percent (8%) of the residual variance. The best interaction model, as determined by the lowest AIC, shows that the influence of rainfall on parasite counts changed depending on whether it was considered from the perspective of the parasite type or the data year. Johnson et al. (2013) suggest that infection risk in complex ecosystems is determined by the interplay of host, parasite, and environmental factors rather than solely by single drivers operating independently.

The findings reveal that rainfall largely influences the intensity of gastrointestinal parasites, but the effects of rainfall vary for different parasites, parasite troops, and years. In general, higher average monthly precipitation was associated with higher parasite intensity, which supports the idea that moisture is a major factor in the spread of parasites (Shearer & Ezenwa, 2020). Nevertheless, this positive impact was statistically significant only for Strongylid nematodes, not for other parasite taxa (Banda et al., 2024). Especially in 2023, there was a positive correlation between mean monthly rainfall and Strongylid intensity. During the rainy seasons, Strongylid intensity was high, indicating that the moist stages of these soil-transmitted helminths were promoted by rainfall and, consequently, infection levels rose (Banda et al., 2024). Blersch et al. (2021a) concluded that precipitation was the main driver

of the seasonal aspect of pathogen prevalence and that it led to the high intensity of Strongylid nematodes.

Similarly, Akinyi et al. (2019) observed that prolonged rainfall periods are associated with increased risk of helminth infection in wild baboons. This study concurs with the former and latter studies that the majority of pathogens, especially those with free-living stages, thrive under warm and wet conditions (Blersch et al., 2021a; Banda et al., 2024). Chapman et al. (2005) observed that “connections between weather and disease are well established” and argued that numerous parasitic diseases peak during specific rainy seasons or weather events. The present study findings support some models by providing evidence of a strong rainfall-driven increase in Strongylid infections (Blersch et al., 2021a). Rainfall has different effects on different parasite species (Benavides, 2012). The lack of a rainfall effect on most taxa indicates that Strongylid nematodes were the only taxa able to take advantage of the wet conditions. In contrast, other parasites may have been regulated by different factors or may have had more stable background infection levels (Benavides, 2012). Habig et al. (2021) found that helminth infection patterns in baboons varied across years and seasons, and that some parasites showed peak infection in one season of one year but not in another. This complexity was supported by Mignatti et al. (2016), who used time-series data from two helminth species infecting a natural herbivore (*Oryctolagus cuniculus*: European rabbits) and investigated the contributions of climate change and immunity to the long-term and seasonal dynamics of infection in Scotland. The study's findings revealed that climatic effects on parasite dynamics depended on host factors.

The influences of past monthly rainfalls were investigated to see if there were any delayed effects on parasite intensity. Models with lagged rainfall did not perform better than the model with contemporary rainfall; lag-1 and lag-2 rainfall were almost identical in terms of fit ($\Delta\text{AIC} < 0.2$), whereas the combination of current and lagged terms significantly degraded performance ($\Delta\text{AIC} > 26$), probably due to collinearity. Therefore, parasite responses were mostly contemporaneous, which is consistent with a semi-arid savanna, where each rainy season essentially “resets” ecological conditions. Parasite intensity increased in the same season as rainfall; thus, this is consistent with patterns reported in other primate and ungulate systems, where fecal egg counts rise within weeks of rainfall onset when humidity and temperature are at optimal levels (Chapman et al., 2005; Blersch et al., 2021b). Quite importantly, “no lag effect” reflects the main statistical model, in which effects are biologically indistinguishable rather than biologically irrelevant. Past monthly rainfall was in line with current rainfall in the two-year dataset; thus, it was

difficult to separate the different effects. More extended or detailed studies may reveal subtle delayed influences. This implies that, in this particular ecological environment, the current rainfall may not be more important for initiating the growth and spread of infectious stages than rainfall from previous months. One cannot, however, rule out the biological significance of delayed effects, given the lagged models' comparable performance; they are not statistically better predictors in this case.

Conclusion

Although being parasite-specific, increased rainfall played a significant role in shaping baboon gastrointestinal parasite intensity in Chacma baboons in a semiarid savanna ecosystem. Using linear mixed-effect modelling, the study demonstrated that parasite intensity was influenced by a three-way interaction among rainfall, year, and parasite type, highlighting the complexity of the host–parasite–environment system. Among the parasites, Strongylid nematodes showed a pronounced increase in intensity over time with higher rainfall, particularly in 2024. Lagged monthly rainfall effects did not outperform contemporaneous rainfall parasite intensity, indicating that parasite responses were largely immediate in this system.

Recommendations

It is recommended that future research incorporate additional climatic variables (temperature and humidity) and biological factors (host health, immune status, and behavioural data) in constructing fixed linear models to determine all inter-annual drivers of parasite outbreaks, if possible. Integrating host health, immune status, and behavioural data may further strengthen inference.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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