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African Journal of Ecology

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African Journal of Ecology

RESEARCH ARTICLE

Rainfall Variability Shapes Lion Movement and Home Range Dynamics in Three Kenyan Parks

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Received: 2 October 2024 | **Revised:** 12 December 2024 | **Accepted:** 24 December 2024

Funding: This work was supported by Leo Foundation and Savannah Tracking for providing the collars used in this study. This work was supported by the Department of Atomic Energy, Government of India, Project Identification No. RTI 4006. MTT thanks the European Research Council (ERC) for funding under the European Union's Horizon 2020 research and innovation program (grant agreement 802933). We also thank all reviewers for providing constructive feedback that greatly improved this manuscript.

Keywords: adaptive management | Africa | behaviour | climate change | conservation | movement | *Panthera leo* | site-specific

ABSTRACT

Variation in climatic conditions is expected to impact the distribution and abundance of herbivore species, which may, in turn, influence African lions (*Panthera leo*) ranging behaviour. This necessitates proactive management of lion populations, as ecosystems may exhibit site-specific responses to these variations. Using satellite and GPS-GSM data from 10 lions collared in three different national parks in Kenya—Meru, Nairobi, and Lake Nakuru—we calculated monthly home ranges and distance moved and studied how these were influenced by rainfall. Across all parks, lions increased their distance moved with an increase in rainfall, and male lions covered larger distances than females. Model comparisons revealed that lions in Lake Nakuru significantly expanded their home ranges with higher rainfall compared to those in Nairobi; however, lions in Nairobi covered larger distances than those in Lake Nakuru. Lions in Meru had larger home ranges compared to the other two parks, but the effect of rainfall on their home range size and movement was not significantly different from the other two parks. Our results give insight into the site-specific influence of rainfall on lion home range and movement across the parks. We call for prioritisation of conservation efforts and a site-specific, tailored approach to lion conservation and management.

1 | Introduction

African lions (*Panthera leo*) are apex predators that play a crucial ecological role and hold significant cultural and economic value within their habitats (Lindsey et al. 2017; Ripple et al. 2014). They are, however, classified as vulnerable on the Global Red List of the International Union for Conservation of Nature (IUCN) (Nicholson et al. 2023). In Kenya, lions are considered nationally endangered due to ongoing population decline (Kenya Wildlife Service 2020a). This decline is largely driven by retaliatory killings due to livestock depredation and habitat loss resulting from anthropogenic activities, such as agricultural and urban development (Kenya Wildlife Service 2020a). Additionally, changes in prey density, driven by variability in rainfall due to climate change, also contribute to this decline (Bauer et al. 2015; Loveridge et al. 2022). To counteract these threats, protected areas (PAs) have been advocated as essential for lion conservation, as they allow for focused, site-specific protective measures. More so, fencing of PAs is a common measure aimed at preventing lion predation on livestock, human encroachment, and poaching (Lindsey et al. 2017; Packer et al. 2013). However, while fencing can reduce conflict and poaching, it is controversial because it leads to habitat fragmentation and reduced connectivity, increasing the vulnerability of lion populations to environmental and demographic stochasticity (Chege et al. 2024; Miller et al. 2015). Furthermore, fencing may alter the ranging behaviour and spatial distribution of species, leading to disruptions in ecosystem structure and function (Cozzi et al. 2013; Durant et al. 2015). These disruptions are likely to be exacerbated where climate change increases the frequency and severity of extreme weather events like droughts (Shrader, Pimm, and van Aarde 2010). Consequently, managing fenced populations can be costly, not only due to costs related to fence maintenance but also due to the need for adaptive management of the enclosed populations and habitats (Creel et al. 2013).

Currently, more than 50% of the existing lion range in Africa occurs within PAs, with the rest distributed across human-dominated landscapes (Lindsey et al. 2017). Most of this range comprises arid savannah ecosystems with highly variable precipitation (Riggio et al. 2013). The phenology of these arid savannahs is closely tied to annual rainfall, affecting surface water and forage availability (Western 1975). These factors, in turn, influence herbivore dynamics, which shape lion home ranges (Smuts, Hanks, and Whyte 1978). A home range is defined as the area that animals move through during normal activities such as resource acquisition and reproduction (Burt 1943). It can be quantified by a utilisation distribution, which describes the frequency distribution of an animal's location in an ecosystem (Worton 1989). The 50% utilisation distribution is often considered the core and most critical area within the entire home range (Powell 2000). Factors such as prey availability, population density, sex, age, seasonality, presence of livestock, intra- and interspecific interactions also affect home range size and movement patterns (Chesson et al. 2004; Huqa 2015; Loveridge et al. 2009; Tumenta et al. 2013; Valeix, Loveridge, and Macdonald 2012).

In recent years, Kenya has experienced climate variability characterised by rising temperatures, frequent droughts, and unpredictable rainfall patterns—reduced rainfall during long rains (March–May) and increased rainfall during short rains (October–December) (Funk et al. 2023; Palmer et al. 2023). These climatic shifts have led to loss of suitable habitats and decline in wildlife populations (Ogutu et al. 2016). Consequently, it is essential that managers improve their ability to anticipate these changes by understanding short-term responses of individuals and populations to precipitation. Particularly because ecosystems vary and local conditions can influence lion home range size and movement in different ways (Lesilau et al. 2021; Tuqa et al. 2014; Turner et al. 2022). Often strategies for lion management and conservation are employed uniformly, that is, as a 'one-size-fits-all' approach across landscapes, which may not be suitable in the long term, since environmental factors may have site-specific influence on species (Chege et al. 2024; Pettorelli et al. 2014). Thus, knowledge of a species ranging behaviour and factors that influence home range size is crucial for understanding its ecology, distribution, and population dynamics, as well as for designing effective conservation and management strategies (Woodroffe and Ginsberg 1998).

Therefore, our study aims to contribute to the analysis of the relationship of rainfall with lion home range and movements. It explored the influence of rainfall on lion home range size and movement patterns in three national parks (NP) in Kenya: Meru NP, Nairobi NP, and Lake Nakuru NP. These parks are characterised by varying climatic conditions, providing a comparative, site-specific framework for understanding how rainfall may influence lion behaviour. Our main objectives were to determine: (1) home range and distance moved (i.e., movement) by lions in each park; (2) the influence of rainfall on (a) lion home range and (b) distance moved. We hypothesised that lions in Meru NP would have larger home ranges and more extensive movements since the park has limited fencing (Figure 1), a lower herbivore biomass density (Table S1), and irregular rainfall patterns that would affect surface water availability. For Nairobi NP we hypothesised that rainfall would have no significant effect on lion home range size but would be significantly correlated with movement. This hypothesis is based on a previous study by Lesilau et al. (2021) that found no difference between wet and dry season home ranges but found seasonal variation in lion movements. For Lake Nakuru NP, we hypothesised that there would be no significant correlation between rainfall, home range size, and distance moved since the park is fully fenced and has a substantial prey base. We defined the following research questions:

1. What is the monthly home range (50% KDE, 95% KDE and 100% MCP) and monthly average of distance moved in 24 h of lions in each park?
2. Are there differences between the home ranges and distance moved in the three parks and between male and female lions?
3. What is the relationship between monthly rainfall and home ranges and distance moved in each of the three parks?
4. Are there differences in how rainfall influences home range and distance moved across the three parks?

The results of our study may inform the development of site-specific management strategies for lion populations in Kenya and similar environments.

2 | Materials and Methods

2.1 | Study Area

Meru National Park (MNP), located close to the foothills of Mount Kenya, was established in 1957 and covers an area of 884 km^2 (Figure 1). It is situated between latitude 0°20′ ~ 0°10′ S and longitude 38°0′ ~ 38°25′ E and lies at an altitude ranging from 300 to 1000 m above sea level (Narisha 2018). The park has an electric fence ~86 km on the western and southern boundaries where it borders community areas and is unfenced on the north and south eastern sides where it borders Kora NP, Bisanadi, and North Kitui

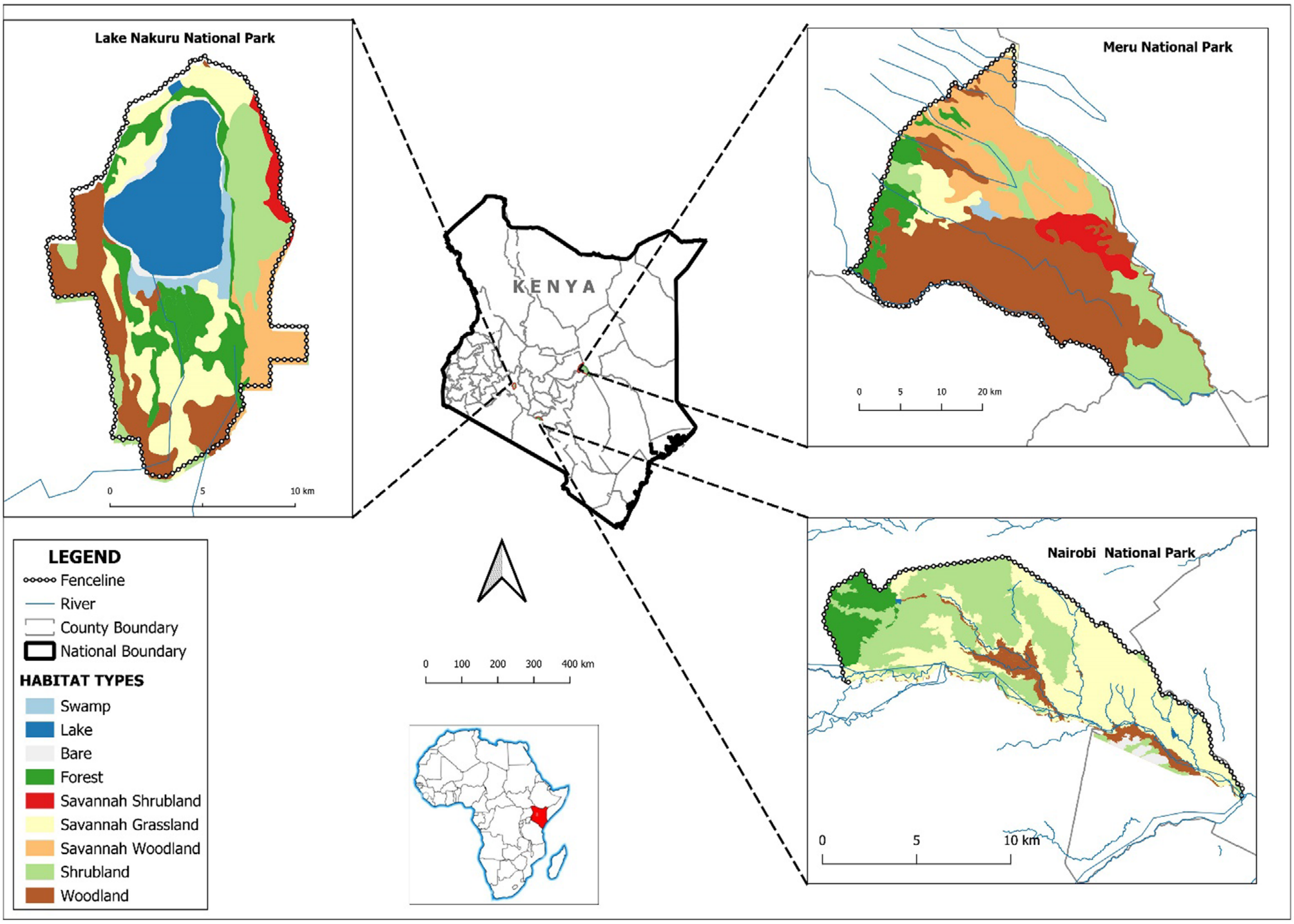

FIGURE 1 | Map showing the location of the three study areas (For further information regarding the study areas see Table S1).

national reserves, respectively. The annual rainfall ranges between 200 and 724 mm, characterised by two rainy seasons, the long rains in the months of March–May and short rains from October to December (Narisha 2018). The pattern is erratic, with some years having more than double the mean annual rainfall than others, and dry periods can last between 4 and 8 months (Kariuki et al. 2020). The park receives differential precipitation, which decreases from north to south, which characterises the vegetation (Narisha 2018). The park has a network of 14 permanent rivers, but due to water extraction upstream, most dry up during the dry season (Kenya Wildlife Service 2007).

Nairobi National Park (NNP) is located southwest of Nairobi City and MNP, was established in 1946, and has an area of 117 km^2 (Owino et al. 2011) (Figure 1). It is situated between latitudes 10 20′–10 26′S and longitudes 360 50′–360 58′E and lies at an altitude ranging from 1500 to 1800 m above sea level. NNP is enclosed by an electric fence ~73 km on the three sides that border Nairobi city, while the southern section is open to allow wet season wildlife dispersal into the Athi-Kapiti plains, an area of 2200 km^2 pastoralist rangeland (Kenya Wildlife Service 2020b). The annual rainfall in NNP ranges between 726 and 911 mm in two seasons: March to May (long rains) and November to December (short rains) (Lesilau 2019; Kenya Wildlife Service 2005). The park has several rivers, and dams, with two main rivers that is, Mbagathi and Mokoyiet, and three dams; Hyena, Nagolomon, and Athi basin having water year-round (Kenya Wildlife Service 2020b).

Lake Nakuru National Park (LNP) is located northwest of NNP, was established in 1968 and has an area of 188 km^2 (Figure 1). It is situated between latitude 0°18′S and 0°27′S; longitude 36°1.5′E and 39°9.25′ E, and lies at an altitude ranging from 1760 to 2080 m above sea level on the floor of the East African Rift Valley (Mwasi 2002). LNP is fully fenced by a 78 km long electric fence (Kenya Wildlife Service 2018), which was installed to protect the critically endangered black rhino (*Diceros bicornis*) population (Mwasi 2002). The size of the soda lake in LNP fluctuates depending on precipitation levels, and in 2022 it covered ~56 km^2. The annual rainfall ranges between 876 and 1050 mm, distributed in a bimodal pattern in April-June and October-December (Ogutu et al. 2012; Kenya Wildlife Service 2011). Five seasonal rivers drain into LNP (Njoro, Lamuriak, Makalia, Naishi, and Nderit), plus perennial springs along the eastern shoreline (Kutliek 1979). These provide natural drinking water for wildlife (Kutliek 1979).

2.2 | Home Range and Distance Moved Data

We used collar data from 10 adult lions that were collared with satellite and GPS-GSM collars from African Wildlife Tracking (AWT) in Pretoria, South Africa, and Savannah Tracking (ST) in Nairobi, Kenya. The lions were collared at different periods: 2 males and 1 female in MNP between 2016 and 2019; 2 males and 2 females in NNP between 2017 and 2021; and 2 males and

1 female in LNP between 2019 and 2023 (see Table S2). Animal capture and handling protocols for darting and collaring were carried out by and as per the regulations and procedures of the Kenya Wildlife Service, a government institution with the mandate to conserve and protect wildlife in Kenya. The lions were immobilised by darting with an air-powered Dan Inject rifle, administering an intramuscular injection of ketamine and medetomidine HCl. After approximately 40 min to 1 h, the immobilisation was reversed with an intramuscular injection of Atipamezole HCl.

Since the objective of collaring varied (e.g., management, research, alleviating conflict), the collars had different reporting schedules (i.e., 1, 2 and 3-h). To standardise the data, we reduced the number of readings to 8 per day: four random readings during the day (0600–1800) and four at night (1801–0559).

Due to various data gaps during each collaring period, caused by collar malfunction, we focused on analysing the influence of rainfall on lion home range at a fine scale (i.e., monthly). Only months with 28 or more days of data were included in the analysis.

The monthly home range size of each collared lion (in km^2) was determined by calculating Minimum Convex Polygons (MCP) and Kernel Density Estimation (KDE) using the Geo-spatial Modelling Environment software (Locher and Lindenberg 2016). MCP creates a polygon by connecting the outer GPS locations, while KDE considers density estimations of GPS locations (Powell 2000). We determined the resolution bandwidth with least-squares cross-validation for fixed-kernel home ranges (Seaman and Powell 1996). The boundaries of the home range areas were defined as 100% MCP and 95% KDE for point distributions, and the core home range as 50% KDE (Powell 2000). While KDE is a powerful tool for estimating home ranges, it has the limitation of relying on kernel density estimations that do not account for landscape features, animal movement paths, or boundaries (Silva et al. 2018), which may be problematic for areas with hard boundaries, such as fences/towns, and internal structures from which animals are excluded (Briers-Louw, Verschueren, and Leslie 2019). MCP, on the other hand, is sensitive to sample size and point pattern shape, and both methods may overestimate home ranges (Downs and Horner 2008; Silva et al. 2018). Therefore, consistent with other studies, that is, Laizer, Tarimo, and Kisui (2014) and Lehmann et al. (2008), we clipped out areas where the MCP and KDE covered the lake or outside the park boundary into urban areas, as they do not contribute to the home range.

We calculated the distance moved as the Euclidean distance between following GPS fixes within 24 h (Hunter 1998) and then summed these daily distances to obtain the total distance moved over a month (in km).

2.3 | Rainfall Data

We downloaded daily rainfall time series data (in millimetres) from Climate Hazards Group Infra-Red Precipitation with Station data (CHIRPS) from www.climate-engine.org. This is a global precipitation dataset with high spatial (1 km) resolution that combines satellite imagery with in situ station data to produce accurate and detailed precipitation estimates. The rainfall data corresponded to the complete collar data period 2016–2023. We then calculated the total amount of rainfall per month per park in mm. These data were used to analyse the difference in rainfall between parks. We calculated the average monthly rainfall and the change in monthly rainfall over the period 2016–2023. Also, the seasonal change in monthly rainfall within a year averaged over all years was calculated.

2.4 | Statistical Analysis

All statistical analyses were carried out using R version 4.2.0 (R Core Team 2022). For describing and showing our results, we used the standard statistical and graphic functions. Scatterplots were made with the function *scatterplot()* of the package *car* (Fox and Weisberg 2019). A correlation matrix was generated with the function *rcorr()* of the package *Hmisc* (Harrell Jr 2024) to test for correlation between home range and distance moved for all lions.

To test for differences in home range and movement across the three parks and the influence of rainfall on both, we began by log-transforming the dependent variables to achieve normal distribution. We built linear mixed effect models (lme) using the function '*lmer()*' from the *lme4* package (Bates et al. 2015). In all cases, lion identity was included as a random effect factor. We performed preliminary tests checking the effect of sex on home range and distance moved using *boxplot()* and lme. Then, we checked the influence of rainfall on sex using lme. We further assessed the variation in rainfall across the parks by performing a regression analysis and using *scatterplot()*. These tests were carried out to determine the parameters that would be included in *full* linear mixed models to avoid overfitting and to ensure that the *full* models would be parsimonious since our dataset was quite small.

To facilitate a systematic comparison of the effect of rainfall on lion home range between the parks, we then built *full* LME models with home range as the response variable and the interaction between rainfall and park as the fixed effects.

$$log(\text{Home range}) \sim \text{Rainfall} * \text{Park} + (1 \mid \text{LionID}).$$

In the case of distance moved, the mixed models also included sex as a fixed effect variable since there were differences between the distance moved by males and females.

$$log(\text{Distance}) \sim \text{Rainfall} * \text{Park} + \text{sex} + (1 \mid \text{LionID}).$$

Visual inspection of residual plots for all models did not reveal deviations from homoscedasticity or normality.

The results of all the *full* LME models are given in the Tables S7–S10. For the sake of clarity, these models were summarised in tables that facilitated comparison between the parks. In these tables, we included a descriptive 'Diff.' column with letters to indicate differences between parks. For instance, where rainfall significantly influenced home range or distance moved differently, an 'A' in the Diff. column for one park and 'B' for another would indicate that the influence of rainfall in these two parks is statistically different. Conversely, park(s) that had the same letter would indicate no statistically significant difference from the other park(s) sharing that letter.

3 | Results

3.1 | Home Range and Distance Moved

Table 1 below shows a summary of the mean home range and distance moved by both male and female lions in each park. Correlation tests indicated a strong correlation among the three home range measures (Pearson Correlation: $r > 0.8$; $p < 0.001$) and a moderate correlation between the home ranges and distance moved (Pearson Correlation: $r > 0.5$; $p < 0.001$) (Table S3).

An examination of differences in lion home range size between parks revealed no significant differences for the KDE 50% and MCP 100%. However, for KDE 95% lions in MNP appeared to have significantly larger home ranges compared to those in NNP and LNP (Tables 2, S4 and S5). For distance moved, NNP lions covered larger distances than those in LNP (Table 3).

Notably, the monthly lion home ranges for the female in LNP spanned most of the park, whereas in MNP and NNP the home ranges were restricted to specific sections of the park (Figures 2–4).

When comparing home range sizes between sexes, no significant differences were found. However, there were significant differences in the distance moved between male and female lions ($t = 3.17$; $df = 7.7$; $p = 0.01$; Table S6).

3.2 | Relationship Between Rainfall, Home Range and Distance Moved

3.2.1 | Rainfall

There was no significant variation in rainfall across the years 2016 to 2023 ($F_{[1286]} = 0.02$; $p = 0.898$). However, we found significant differences in the amount of monthly rainfall across the three parks ($F_{[2285]} = 14.14$; $p = < 0.001$), with LNP having higher rainfall compared to NNP and MNP (Figure S1). The seasonal change in rainfall was different between the three parks (ANOVA: interaction between month and park: $F_{[22,252]} = 11.21$; $p < 0.001$). For LNP there was no dry period between June–September, while it was present in MNP and NNP (Figure 5).

TABLE 1 | Mean female and male lion home range and distance moved estimates for Meru (MNP), Nairobi (NNP), and Lake Nakuru National Park (LNP), using Kernel density and minimum convex polygon.

	Female home range (km^2)				Male home range (km^2)			
National Park	**KDE 50%**	**KDE 95%**	**MCP 100%**	**Distance moved (km)**	**KDE 50%**	**KDE 95%**	**MCP 100%**	**Distance moved (km)**
MNP	27.7 [8–68]	101.4 [36–214]	77.2 [32–162]	117.3 [79–191]	25.1 [1–55]	101.3 [10–188]	76.4 [15–128]	122.7 [56–155]
NNP	8.0 [1–16]	33.6 [11–58]	30.4 [12–46]	109.8 [70–172]	12.5 [2–37]	49.3 [12–129]	46.3 [11–106]	166.3 [89–275]
LNP	14.9 [1–59]	53 [11–28]	45.3 [9–111]	110.2 [35–219]	17.8 [2–44]	59.8 [9–125]	50.9 [8–122]	145.2 [55–368]

Note: Values in square brackets indicate the range, that is, minimum and maximum.

TABLE 2 | Estimates of the intercept and regression coefficient of the relationship between KDE 95% home range and rainfall per month per national park based on the mixed linear model with lion identity as random effect factor.

KDE 95 km^2; conditional R^2: 0.272; marginal R^2: 0.168						
	Estimate	**Std. error**	***df***	***t* value**	***Pr*(>|*t*|)**	**Diff.**
Intercept						
MNP	4.2470	0.2276	30.0	18.66	**< 0.001*****	A
NNP	3.6530	0.1619	14.0	22.56	**< 0.001*****	B
LNP	3.6100	0.1715	11.1	21.05	**< 0.001*****	B
Regression coefficient						
MNP	0.0026	0.0017	173.4	1.51	0.132	AB
NNP	−0.0005	0.0009	171.0	−0.50	0.617	A
LNP	0.0031	0.0011	168.7	2.81	**0.006****	B

Note: $Pr(>|t|)$: Probability of estimate being different from zero; Diff.: The statistical difference ($p < 0.05$) between the estimates: Estimates with the same capital letter are not different.
***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

TABLE 3 | Estimates of the intercept and regression coefficient for the relationship between distance moved and rainfall per month per national park, based on the mixed linear model with lion identity as random effect factor.

Distance moved in km; conditional R^2: 0.236; marginal R^2: 0.186						
	Estimate	**Std. error**	***df***	***t* value**	***Pr*(>|*t*|)**	**Diff.**
Intercept						
MNP	4.4490	0.1359	27.2	32.74	**<0.001*** **	AB
NNP	4.7220	0.0870	12.3	54.31	**<0.001*** **	A
LNP	4.4650	0.0980	9.4	45.58	**<0.001*** **	B
Regression coefficient						
MNP	0.0014	0.0010	170.6	1.38	0.168	AB
NNP	0.0000	0.0005	171.3	0.01	0.995	A
LNP	0.0017	0.0006	169.5	2.71	**0.008** **	B
Sex						
Difference male–female	0.3037	0.0834	6.5	3.64	**0.009** **	

Note: Pr(>|*t*|): Probability of estimate being different from zero; Diff.: The statistical difference ($p<0.05$) between the estimates: Estimates with the same capital letter are not different.
***$p<0.001$; **$p<0.01$; *$p<0.05$.

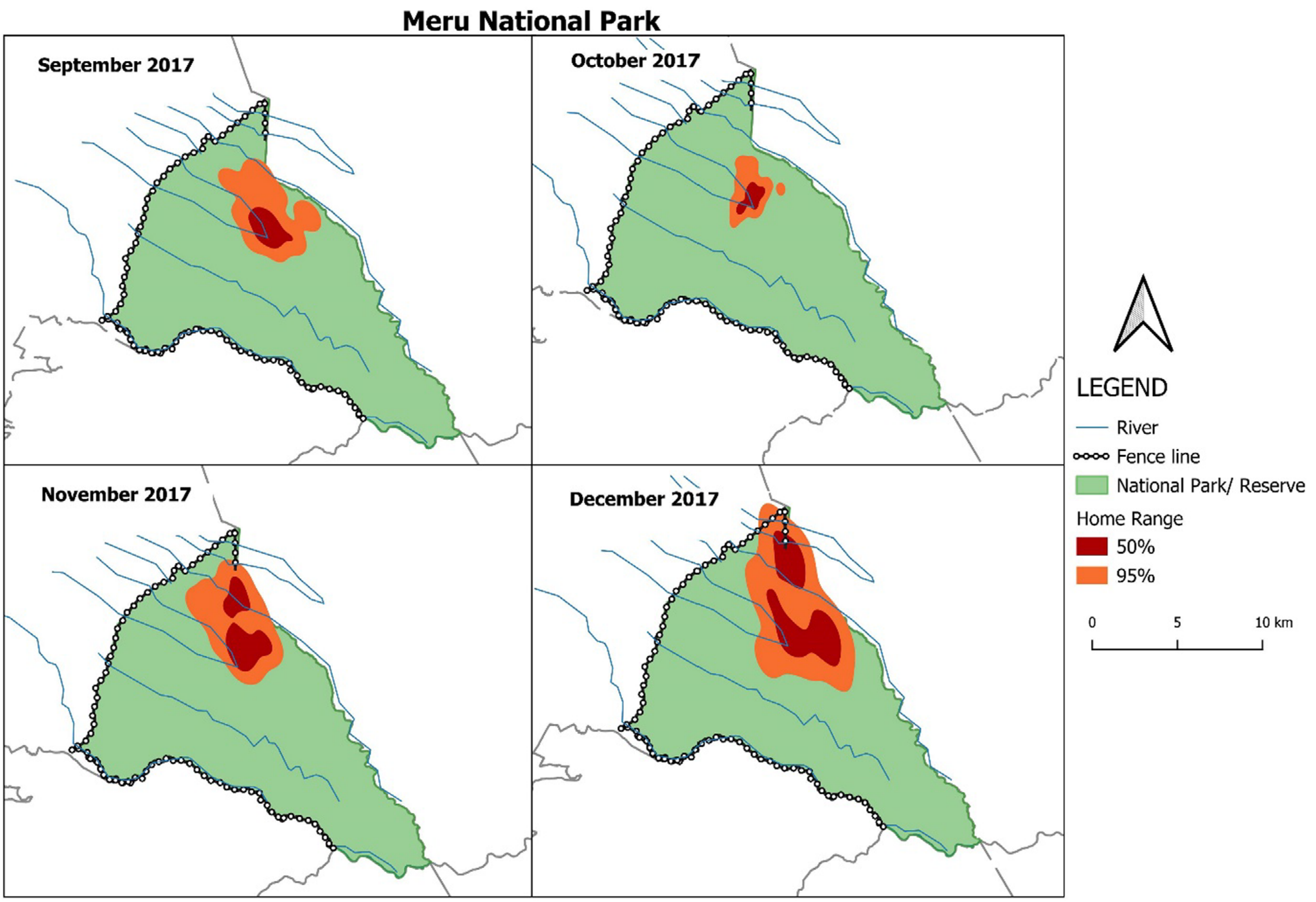

FIGURE 2 | Female lion home range in Meru National Park from September to December 2017.

When examining for the effect of rainfall on lion home range and movement, given the correlation among the three different home range estimates (Table S3) and the consistent effect of rainfall across these estimates, we focus on the results of KDE 95% estimate in the main text. Additional results are provided in the Figures S2 and S3, Tables S4 and S5. Our choice for focussing on KDE 95% was based on this dataset following a more normal distribution.

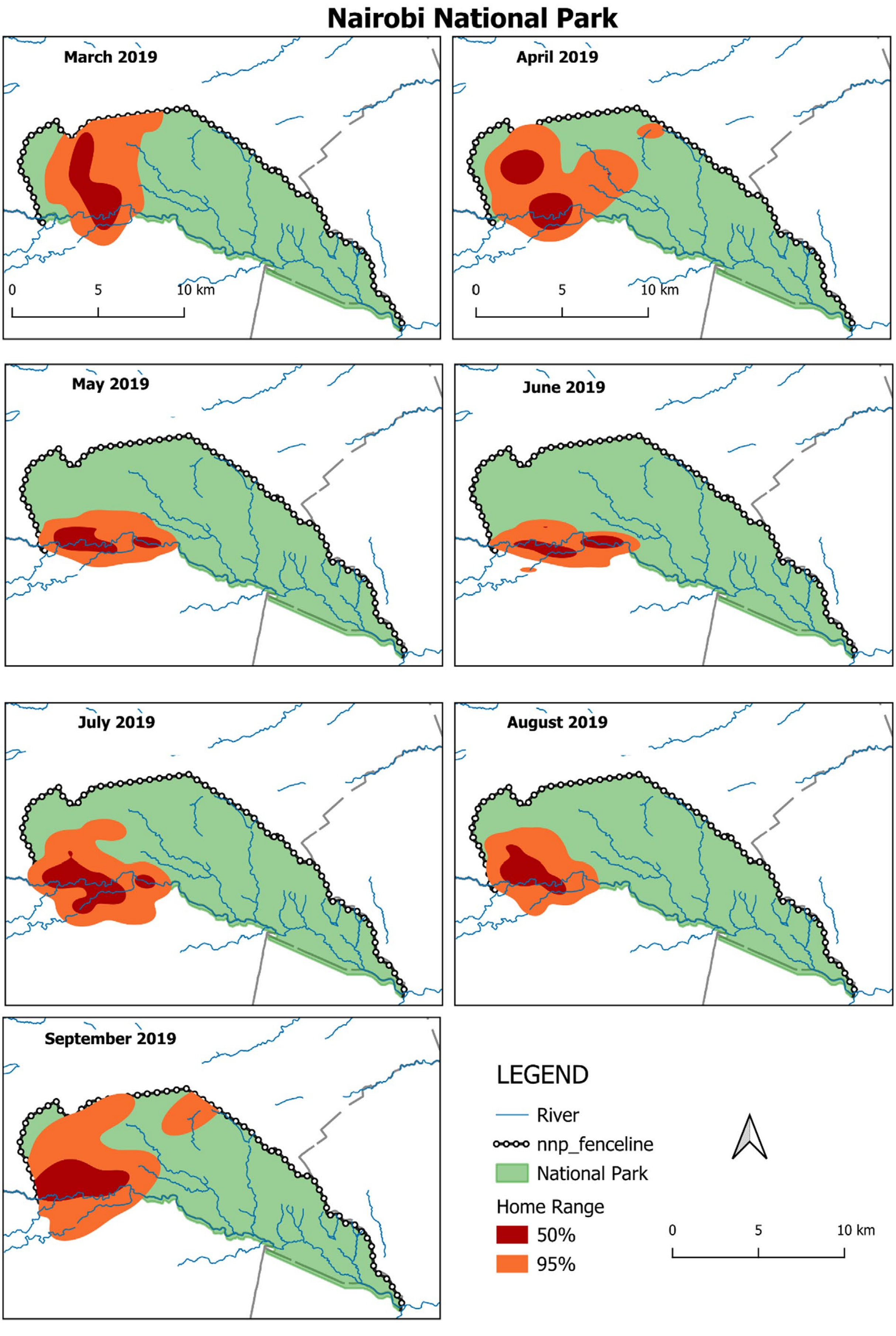

FIGURE 3 | Female lion home range in Nairobi National Park from March to September 2019.

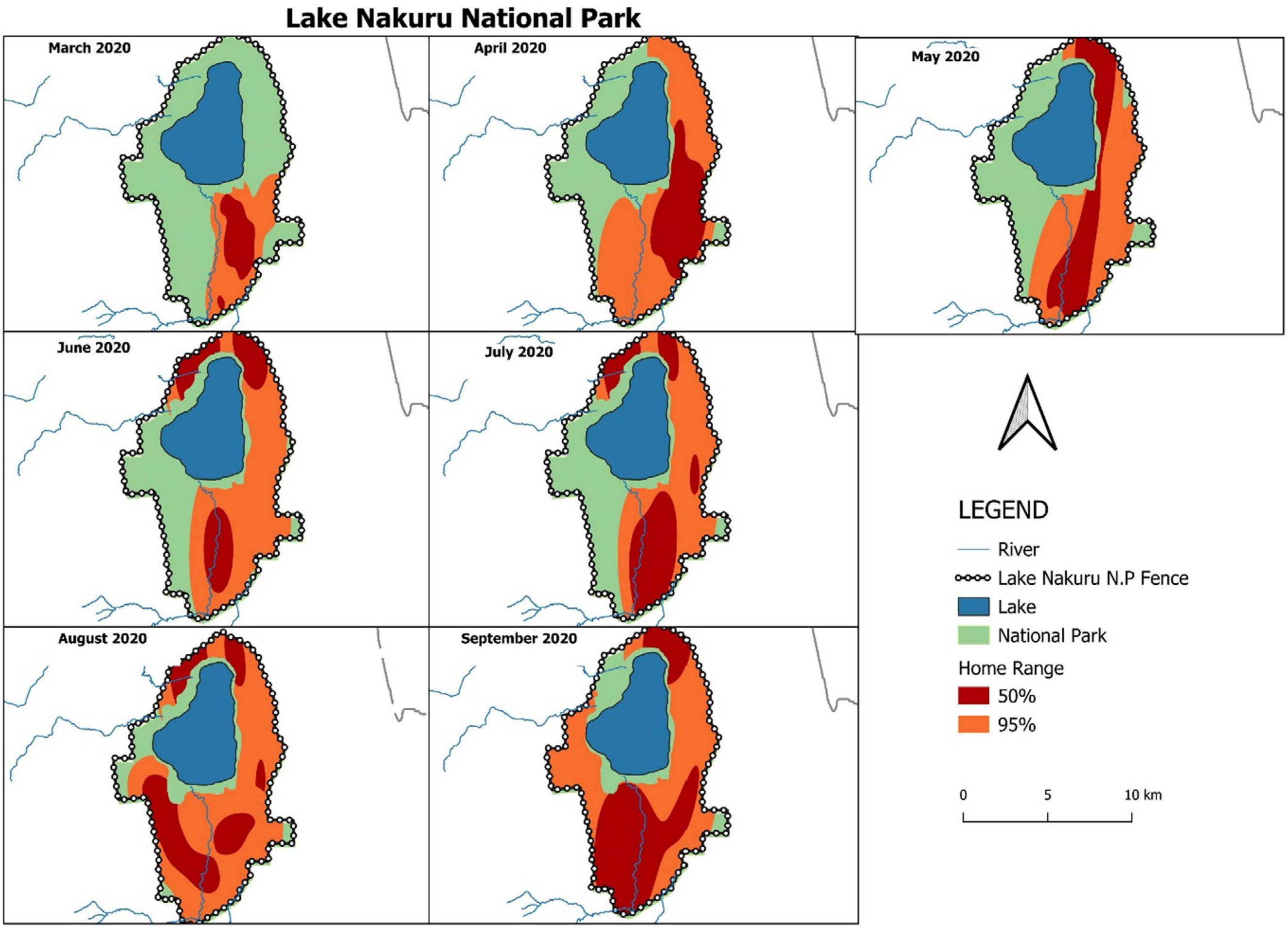

FIGURE 4 | Female lion home range in Lake Nakuru National Park from March to September 2020.

3.2.2 | Rainfall and Sex

The effect of rainfall on home ranges was similar for both sexes that is, no significant trend, as shown in Figures 6A and S2A,B.

3.2.3 | Rainfall and Home Range

The home range for lions in LNP showed a significant positive trend in relation to rainfall, where it increased with increase in rainfall, while in MNP and NNP the trend was not significant (Figure 7A and Table 2). Model comparisons showed a significant difference in the effect of rainfall on home ranges between LNP and NNP ($p = 0.014$; Tables 2 and S8). The effect of rainfall in MNP was not significantly different from the other two parks (Tables 2 and S8).

3.2.4 | Rainfall and Distance Moved

Lions generally increased the distance moved with higher rainfall across all parks, but only in LNP this increase is significant (Figure 7B and Table 3). Male lions covered significantly larger distances than females ($p = 0.009$; Table 3).

Model comparisons revealed that while lions in NNP covered larger distances, the effect of rainfall on distance moved was significantly greater for lions in LNP compared to those in NNP ($p = 0.038$; Tables 3 and S10). No significant differences were found between MNP and the other parks (Tables 3 and S10).

4 | Discussion

4.1 | Home Range and Distance Moved

Comparisons among the three different NP revealed significant differences in lion home range sizes, with lions in LNP and NNP exhibiting smaller home ranges compared to those in MNP. Small home ranges are typical of compact and confined parks, where movement can be restricted by fencing and/or human settlements. Presence of high prey biomass (Table S1) and permanent water sources also contribute to smaller home ranges (Lesilau et al. 2021; Turner et al. 2022). The larger home ranges for the MNP lions, are likely due to the distribution and movement patterns of prey species within the park. Prey distribution in the park is influenced by surface water availability which is limited by a variable rainfall pattern and extraction of water upstream which may cause prey to move more in search of water. Additionally, the park's partial fencing allows for greater mobility of the prey species, which influences the lions' home range size.

Like males, female lions are territorial and will actively defend territories that are contiguous with their home range by fighting

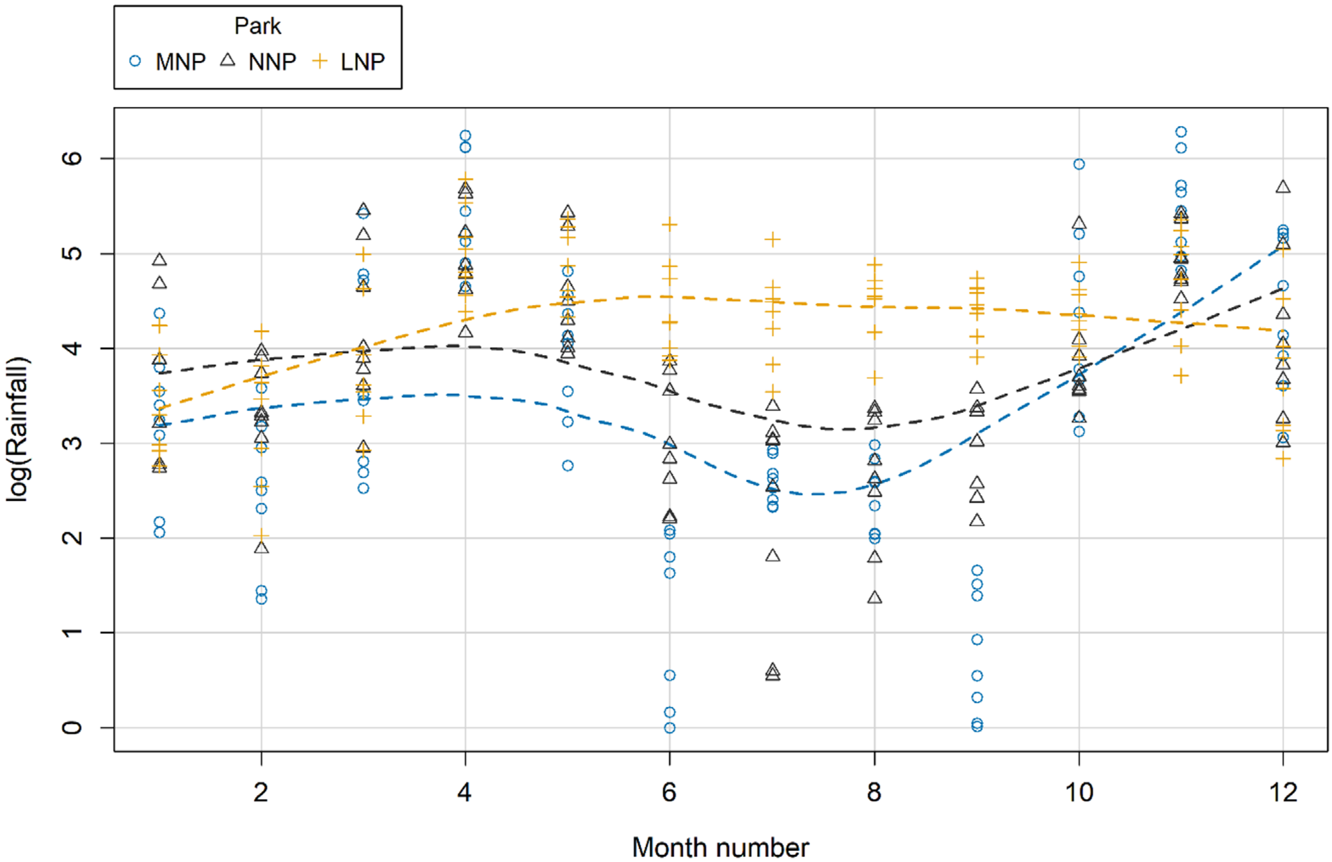

FIGURE 5 | Seasonal change in monthly rainfall in mm across Meru National Park (MNP), Nairobi National Park (NNP), and Lake Nakuru National Park (LNP) from 2016 to 2023. Before log-transforming, 1 was added to the monthly rainfall. Dashed lines are non-linear, smoothed LOESS lines. Month Numbers correspond to 1 for January until 12 for December.

off rivals (Heinsohn 1997). Thus, even though home ranges may overlap, lions will mostly establish home ranges at a sufficient distance from neighbouring prides (Benhamou et al. 2014). However, in areas where space is limited, there are more inter-pride interactions and lions tend to have home ranges that extend over most of the park (Turner et al. 2022). Therefore, for LNP that hosts a small lion population, consisting of only two prides (Beekenkamp 2018; Elliot et al. 2020), it is possible that repeated interactions have fostered a higher degree of social tolerance (McEvoy, Ferreira, and Parker 2022) allowing the female lion to have home ranges that spanned the entire park. This behaviour has also been seen in other small and enclosed areas that is, Turner et al. (2022).

Regarding distance moved, we found that male lions covered larger distances than females, despite there being no significant difference in home range size between the sexes. The larger distances travelled by male lions can be attributed to their need to defend territories that may encompass multiple female prides or to their roaming behaviour during dispersal or pride takeovers (Elliot et al. 2014; Funston 2011).

4.2 | Relationship Between Rainfall, Home Range and Distance Moved

The differences in monthly rainfall across the three parks can be explained by the topographical contrasts, where elevation influences each parks' weather patterns by influencing airflow. In addition, the presence of the lake in LNP affects moisture levels, further contributing to the observed rainfall variation (Obiero and Onyando 2013).

We found a clear relationship between rainfall and lion home range sizes in LNP, which was contrary to our hypothesis given the restricted movement imposed by the electric perimeter fence. Although there are previous records of some movement of both herbivores and lions out of the park due to fence breaches (Wilkinson et al. 2021), the fence was repaired in 2021 and none of the collared individuals breached the fence. While there were no dry periods during the study period within LNP, fluctuations in rainfall may have influenced the lake levels thus altering the availability of the land area through increases in the lake coverage and flooding of grasslands bordering the lake (Hongo and Mulaku 2021; Ogutu et al. 2012). Indeed, Ogutu et al. (2012) found that during periods of increased rainfall, herbivores within LNP moved to grasslands far from the lake and to marsh and alkaline grasslands near the lake during low rainfall periods. This in turn, may influence the movement of lions. Sogbohossou (2011) found that lions in Pendjari Biosphere Reserve, Benin, adjusted their home range during periods of floods where they moved to hilly woodlands and avoided grasslands and swamps.

Climate variability often leads to spatially and temporally heterogeneous effects which can significantly impact animal behaviour through changes in habitat, vegetation structures,

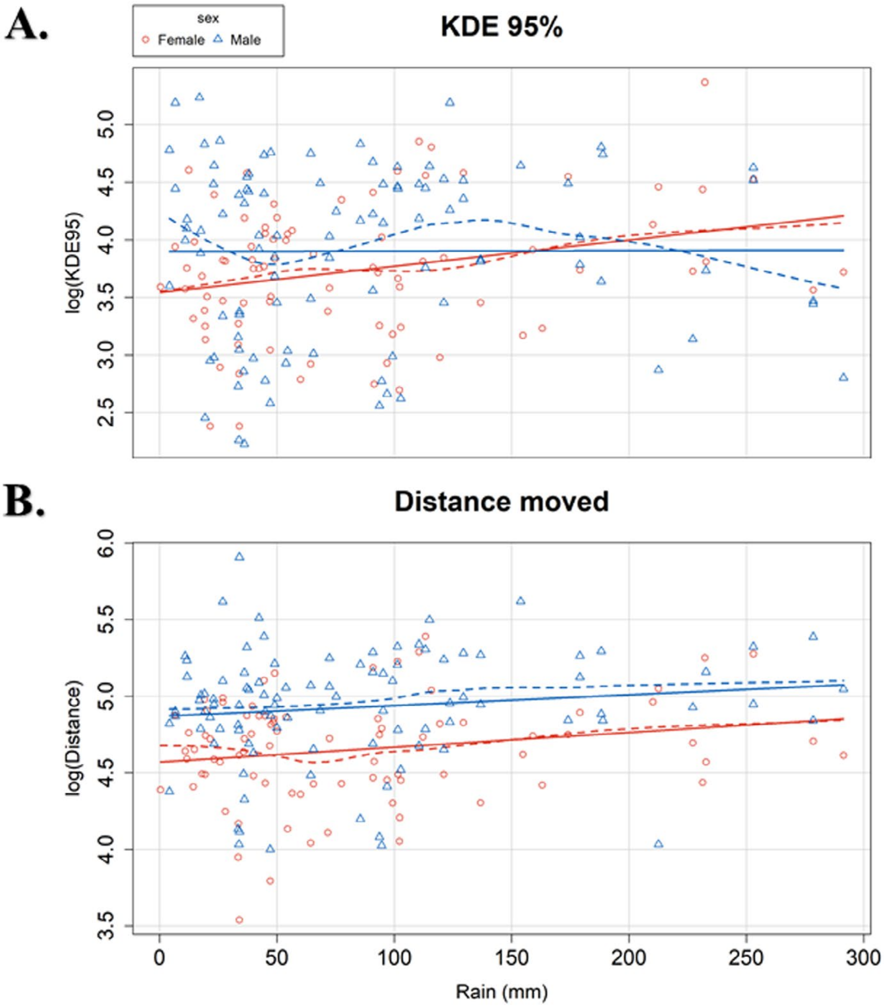

FIGURE 6 | Relationship between monthly rainfall, (A) KDE 95% home range and (B) distance moved in relation to sex for all lions. The solid line represents the linear trend, while the dashed line is the non-linear, smoothed LOESS line.

resource availability and predator–prey dynamics (Rahman and Candolin 2022). Ogutu et al. (2012) showed that, in LNP, the combination of rainfall and temperature variability, surrounding land use changes, and fencing led to changes in prey species population dynamics, abundance, and availability. According to these authors, African buffalo (*Syncerus caffer*), Plains zebra (*Equus quagga*), and Thomson's gazelle (*Eudorcas thomsonii*) numbers increased persistently, during 1970–2011, while Grant's gazelle (*Nanger granti*) and impala (*Aepyceros melampus*) populations initially increased but then gradually declined. African buffaloes replaced waterbucks (*Kobus ellipsiprymnus*) as the predominant species. Consequently, following the dynamics of prey populations, lions may also adapt by adjusting their home ranges in response allowing them to select different prey depending on seasonal availability (Vettorazzi et al. 2022). This was also demonstrated in Hwange National Park, where female lions adjusted their home range in response to specific prey species abundance and distribution (Loveridge et al. 2009). We recommend for further studies on the lion-prey dynamics in LNP to better understand these patterns.

Consistent with Lesilau et al. (2021), we found that rainfall had no significant effect on lion home range in NNP, attributable to a large prey base available year-round. In terms of distance moved, NNP lions covered larger distances than those in LNP, while this could be attributed to the seasonal migration of herbivores out of NNP through the unfenced section (Owino et al. 2011). We found that the effect of rainfall on lion movement was larger for the LNP lions. This results are quite surprising as the movement of lions in LNP is limited by both the fence and availability of land area due to fluctuations in lake levels. It is likely that when rainfall increases the lions in LNP move more in search of both prey (as discussed above) and dry land. Kotze et al. (2018) found that in the Okavango Delta in Botswana availability of dry land is an important resource, with changes in its availability also impacting lion social organisation and reproductive rates. For LNP, being a small and enclosed ecosystem, frequent reduction in available dry land could potentially impact the population. We therefore recommend for a longer term study into the potential impact on the lion population.

Contrary to our hypothesis we did not observe statistically significant differences in the influence of rainfall on home ranges of lions in MNP and those in NNP and LNP. A plausible reason could be attributed to the availability of resources, where all the lions in MNP had their home ranges on the northern

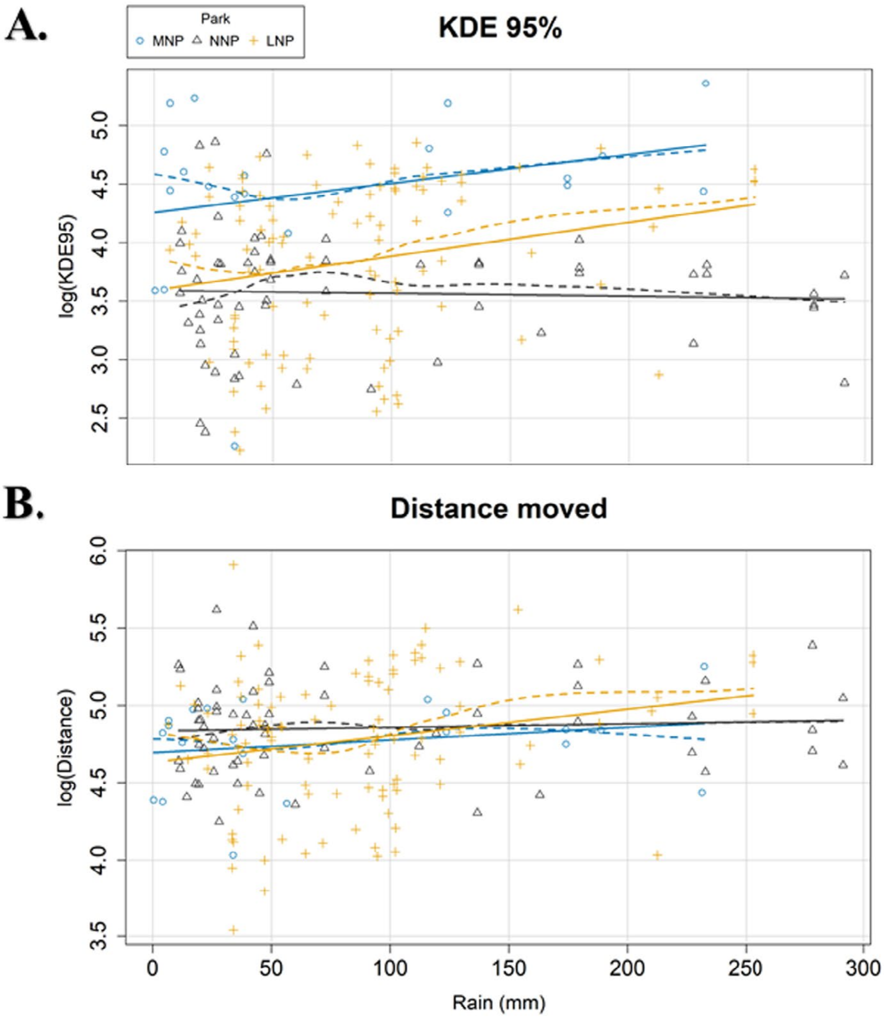

FIGURE 7 | Relationship between monthly rainfall, (A) KDE 95% lion home range and (B) distance moved across Meru National Park (MNP), Nairobi National Park (NNP) and Lake Nakuru National Park (LNP). The solid line represents the linear trend, while the dashed line is the non-linear, smoothed LOESS line.

section of the park. This section receives more rainfall than the rest of the park, resulting in higher concentrations of wild prey (Kennedy 2019). Consequently, while the lion home ranges in MNP are larger, the effect of rainfall on home range and movement is not substantially different from the other two parks.

Our results provide important insights into the influence of rainfall on lion home range across three NP that represent important lion conservation areas in Kenya. These findings have various management implications and highlight the need for prioritisation, as the effect of rainfall is varied. Extreme weather conditions, such as drought, often exacerbate human-wildlife conflicts, especially in areas where protected parks border human settlements (Loveridge et al. 2010). Droughts reduce prey availability and affect the survival of livestock which in turn lowers tolerance to livestock depredation (Peterson et al. 2014; Tuqa et al. 2014). Therefore, understanding how lions respond to environmental factors, such as rainfall, and the subsequent impact on their population and ecosystems, is crucial in designing effective management strategies. For instance, for LNP changes in home range in response to rainfall may not necessarily lead to increase in human lion conflicts due to the perimeter fence. Thus habitat and wildlife population management is of highest priority for this population. Also, as an enclosed park, intensive management to mimic natural processes, informed by regular lion population monitoring, is of prime importance since the population is isolated with signs of genetic degradation reported (Chege et al. 2024).

While, for MNP and NNP changes in home range and increase in distance moved may lead to conflicts in the unfenced sections. Therefore, conflict mitigation measures, education and involvement of communities in conservation should be of higher priority for these two parks. With extreme weather events expected to increase in Kenya in the future, resources are bound to be more scarce leading to increased competition with livestock. More so, because in these parks illegal livestock incursion occurs during dry periods (Waweru John et al. 2021). Thus, implementation of effective and coherent regulations and policies is vital for long-term lion conservation. These policies should aim to minimise human-wildlife conflicts, regulate human activities and conserve wildlife habitats, including dispersal areas.

Finally, we recommend conducting future studies with larger sample sizes to gain a more comprehensive understanding of lions' response to environmental factors. Our findings align with those of Chege et al. (2024), demonstrating that ecological factors have site-specific influence on lions, underscoring the need for adaptive conservation strategies that address local environmental conditions.

Acknowledgements

We thank the Leo Foundation and Savannah Tracking for providing the collars used in this study. This work was supported by the Department of Atomic Energy, Government of India, Project Identification No. RTI 4006. MTT thanks the European Research Council (ERC) for funding under the European Union's Horizon 2020 research and innovation program (grant agreement 802933). We also thank all reviewers for providing constructive feedback that greatly improved this manuscript. Gratitude also goes to Moses Maloba (KWS) for offering technical support in GIS.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.