Assessing the Impact of Human Disturbance on Wildlife Activity Using Camera Trap Data at Cloudbridge Nature Reserve

Panthera onca (Cloudbridge Nature Reserve 2024)

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Abstract

Ecotourism is widely promoted as a sustainable conservation strategy, yet even low-intensity human presence may alter wildlife behaviour and community structure within protected areas. This study investigated how foot traffic influences mammalian activity, temporal behaviour, and species diversity within Cloudbridge Nature Reserve, Costa Rica. Camera traps were deployed across six forest trails over a 344-day period, encompassing 2,150 camera-deployment nights, to compare wildlife responses between high- and low-disturbance trails. Human activity was quantified using camera detections, and mammalian detections were analysed to assess differences in detection rates, daily activity patterns, species richness, and community composition. A total of 1,186 mammalian detections representing 11 species were recorded. Predator and prey detection rates were significantly lower on high-disturbance trails, with predators showing a disproportionately greater reduction than prey. Predator activity patterns also differed between disturbance levels, with high-disturbance trails exhibiting increased nocturnal activity, suggesting temporal avoidance of daytime human presence rather than habitat abandonment. Species richness did not differ significantly between disturbance categories; however, community composition varied markedly, with high-disturbance trails dominated by disturbance-tolerant species and reduced representation of predators. These findings indicate that human foot traffic can alter wildlife behaviour and community structure without immediate species loss. Overall, the study demonstrates that behavioural and compositional metrics provide indicators of human disturbance and highlights the importance of site-specific monitoring for informing adaptive ecotourism management and biodiversity conservation in tropical protected areas.

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Introduction

Every year, billions of tourists visit the world's protected areas, convinced they are helping wildlife—yet their presence can subtly reshape the very ecosystems they aim to protect. Ecotourism is widely promoted as a way to explore pristine landscapes, observe wildlife, and contribute financially to conservation; bringing humans into previously undisturbed habitats such as tropical rainforests, the arctic, and underwater ecosystems (Tablado & Jenni, 2015). Many visitors assume their impact is negligible, reinforcing the perception that tourism inherently benefits nature. In reality, even brief human visits can alter wildlife behavior and habitat use in meaningful ways (Shannon et al., 2017). The global ecotourism market was valued at USD 248.17 billion in 2024 and is projected to grow to approximately USD 945.34 billion by 2034 (Precedence Research, 2025). This paradox highlights a critical challenge: while ecotourism provides essential support for conservation, the belief that it is harmless can obscure the pressures it places on wildlife, emphasising the need to carefully evaluate its ecological consequences (Zhou et al., 2013).

Human traffic can alter wildlife behavior not only in open areas but also in the dense undergrowth of tropical rainforests, where animals may leave the area, become more nocturnal or arboreal, or avoid trails used by humans (Griffiths & Schaik, 1993; Blake et al., 2017). Zhou et al. (2013) found that felids, being particularly timid, are more likely to abandon disturbed habitats, especially due to having larger home ranges so a greater capacity to move, which can reshape predator–prey dynamics and the ecological balance within protected areas. This can lead to altered forest regeneration as herbivore pressure changes and seed dispersal and pollination networks weaken (Vargas et al., 2021). As studies across tropical systems have shown, human presence creates spatial refuges for prey species by deterring large predators (Blake et al., 2017; Muhly et al., 201). These shifts highlight that even non-lethal human activity can have cascading ecological consequences by altering interspecies interactions and balance within ecosystems.

Beyond spatial displacement, human disturbance also drives significant behavioural and physiological changes in wildlife. This "landscape of fear" phenomenon describes how animals increase vigilance and reduce feeding or resting, leading to energy deficits and decreased reproductive success (Ciuti et al., 2012; Chock et al., 2024). In Suriname, Outuber (2021) observed that large cats modified their activity patterns to avoid tourist presence, likely due to disrupted hunting and feeding efficiency, with potential consequences for survival and prey regulation. While other studies have shown that anthropogenic noise and proximity elevate stress and disrupt communication and mating behaviours (Shannon et al., 2017; Vargas et al., 2021). According to Blake et al. (2017) when disturbance sensitive species disappear while human tolerant species increase; over time this results in reduced species richness, dominance of disturbance adapted species and simplifies communities where specialist species are lost. Collectively, these effects demonstrate that human disturbance can compromise animal health, population dynamics, and ecosystem functioning, reinforcing the importance of understanding how even low-impact activities like foot traffic affect wildlife in protected tropical forests.

Protected areas (PAs) are vital for safeguarding biodiversity, and in Costa Rica they cover a significant portion of the country, protecting diverse species. Between 1950 and 1988, about two-thirds of Costa Rica's tropical forest was cleared due to an economic reliance on agricultural exports such as beef, pineapple, coffee, and bananas (Hoffmann et al., 2010). Uniquely, the country has since reversed this trend through conservation legislation, incentives for reforestation, and the promotion of nature-based tourism as a sustainable economic strategy. Today, roughly 28% of Costa Rica's landmass is designated as protected, including national parks that encompass 12% of the nation's area (Miller et al., 2023). Costa Rica's cloud forests are among the most biologically rich and ecologically significant ecosystems in the tropics, supporting high levels of endemism and providing critical ecosystem services such as water regulation, carbon storage, and habitat connectivity across elevational gradients (Bruijnzeel et al., 2011). Locally focused research on human disturbance provides valuable, site-specific insights that can strengthen national conservation efforts. Studies in Costa Rica and Belize have shown that local assessments of visitor impacts offer practical tools for protected-area management (Farrell & Marion, 2001), while Moya Calderón et al. (2025) highlighted that understanding these localised effects is essential for sustaining Costa Rica's expanding ecotourism sector. By generating data on human–wildlife interactions at the reserve level, studies can directly inform national strategies for balancing tourism and biodiversity conservation.

Although research on human disturbance and ecotourism impacts has increased, significant gaps remain—especially in neotropical ecosystems like Costa Rica's cloud forests. Most studies on ecotourism's ecological effects have been conducted in temperate regions of the Global North, leaving tropical systems comparatively understudied (Shannon et al., 2017). Within the Neotropics, existing research often focuses on single species or broad categories of disturbance rather than specific, measurable visitor impacts such as foot traffic. Recent monitoring at Cloudbridge Nature Reserve has begun addressing these gaps. The 2024 study by Bodson provided valuable baseline data on mammal activity using camera traps however over a short period of three months and did not quantify human activity. Building on this foundation, my study continues the monitoring effort with a full year of data collection, allowing for the assessment of seasonal variation in both wildlife and human activity. By focusing specifically on foot traffic—an underexplored form of disturbance—this research aims to ultimately support evidence-based management of protected areas (Blake et al., 2017).

This study will use camera traps to provide a reliable, non-invasive method for studying wildlife presence, abundance, and behavior, making them particularly valuable in dense tropical forests where direct observation is difficult. Their ability to operate continuously across seasons allows for long-term monitoring of species responses to environmental and anthropogenic factors, such as human disturbance (Burton et al., 2015; Blake et al., 2017). As such, camera trapping is increasingly used to assess the ecological impacts of ecotourism and visitor activity in protected areas, making it an ideal tool for quantifying wildlife responses to varying levels of foot traffic within Cloudbridge Nature Reserve.

The aim of this study is to investigate how varying levels of human presence, specifically foot traffic along forest trails, influence wildlife activity and species diversity, richness and composition within Cloudbridge Nature Reserve. By comparing data from trails with differing levels of visitor use, this research seeks to determine whether increased human activity corresponds with changes in detection rates, species richness, or activity patterns among mammals. In addition to overall visitor numbers, group size will also be considered, as larger groups can create disproportionately higher disturbance to wildlife It is hypothesized that trails with higher levels of foot traffic will show reduced wildlife detections and diversity compared to less-frequented trails, reflecting avoidance behavior or temporal shifts in activity. Understanding these relationships will provide valuable insight into the ecological consequences of ecotourism and inform management practices aimed at minimising disturbance while maintaining sustainable visitor access within Costa Rica's protected areas.

Objectives

Primary Objective

Determine how human disturbance (high vs low) influences predator–prey dynamics within Cloudbridge Nature Reserve.

Secondary Objectives

To compare detection rates of predators and prey between high-disturbance and low-disturbance trails as indicators of wildlife habitat use.

To compare the temporal activity patterns of predator and prey species between high-disturbance and low-disturbance trails.

To assess differences in species richness and community composition across high- and low-disturbance trails.

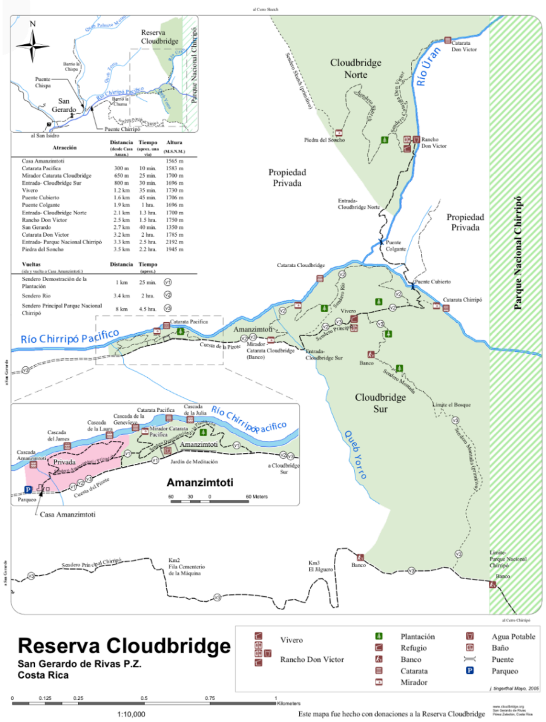
Hypothesis

H1: Mammalian predator and prey detection rates will be lower on trails with higher levels of human foot traffic compared to low-disturbance trails.
H2: Predator activity on high-disturbance trails will be shifted toward nocturnal hours relative to low-disturbance trails, reflecting avoidance of human presence.
H3: Species richness differs between disturbance levels and community composition, with disturbance-tolerant species dominating high-use trails.

Materials and Methods

Study Location

This study was conducted in Cloudbridge Nature Reserve, situated in the Talamanca Mountains of southern Costa Rica (9.451°N, 83.560°W). The reserve lies along the upper Chirripó River, adjacent to Chirripó National Park in the province of San José and spans elevations from approximately 1,550–2,600 m above sea level. The region experiences a humid tropical montane climate, with a mean annual temperature of ~18°C and annual rainfall exceeding 3,500 mm, concentrated from May to November, followed by a drier period from December to April as shown in . The reserve contains a mosaic of regenerating and mature forest due to historical agricultural clearing, including secondary and old-growth cloud forest that support a diverse community of mammals and birds (Cloudbridge Nature Reserve, 2022).



Atracción	Distancia (desde Casa Aman.)	Tiempo (aprox. una vía)	Altura (M.S.N.M.)
Casa Amanzimtoti			1565 m
Catarata Pacifica	300 m	10 min.	1583 m
Mirador Catarata Cloudbridge	650 m	25 min.	1700 m
Entrada- Cloudbridge Sur	800 m	30 min.	1696 m
Vivero	1.2 km	35 min.	1730 m
Puente Cubierto	1.6 km	45 min.	1706 m
Puente Colgante	1.9 km	1 hra.	1696 m
Entrada- Cloudbridge Norte	2.1 km	1.3 hra.	1700 m
Rancho Don Victor	2.5 km	1.5 hra.	1750 m
San Gerardo	2.7 km	40 min.	1350 m
Catarata Don Victor	3.2 km	2 hra.	1785 m
Entrada- Parque Nacional Chirripó	3.3 km	2.5 hra.	2192 m
Piedra del Soncho	3.5 km	2.2 hra.	1945 m

Vueltas (ida y vuelta a Casa Amanzimtoti)	Distancia	Tiempo (aprox.)	
Sendero Demostración de la Plantación	1 km	25 min.	V1
Sendero Rio	3.4 km	2 hra.	V2
Sendero Principal Parque Nacional Chirripó	8 km	4.5 hra.	V3

Fig 1: Map of Cloudbridge Nature Reserve (2005)

Data Collection

Although the full dataset used for analysis represents a complete year of wildlife activity within the reserve, field data collection for this project occurred between 13 October and 21 December 2025 as part of the long-term monitoring programme.

Camera Trap Setup

Wildlife activity was recorded using predominantly Browning Trail Cameras (BTC-7E HP5). Cameras were part of an ongoing monitoring project and were already positioned along established trails, including both public and private routes (El Jilguero and Gavilán). A total of 11 cameras were deployed across the reserve using single, double, or triple setups depending on trail configuration. Cameras were mounted 30–40 cm above the ground, oriented perpendicular to trails to maximise detection of both wildlife and humans. Camera settings included video mode, a 1-second trigger delay, 10-second recording length, medium sensitivity, highest resolution, and Smart IR enabled. Cameras operated continuously, 24 hours per day.

Occasional data gaps occurred due to technical issues, notably at cameras R2 and S3, each missing approximately two weeks of data. No attractants, chemicals, or bait were used.

Data Retrieval and Processing

Cameras were checked every two weeks to replace SD cards, change batteries if necessary, and ensure unobstructed views. Video data were reviewed manually, and detections were recorded in Microsoft Excel (2025) including species, date, time, and number of individuals. To reduce replication, detections of the same species within a 5-minute interval were treated as a single event and abundance noted accordingly. Only medium-sized and large mammals were included in subsequent analyses due to their more reliable detectability and greater likelihood of showing behavioural responses to human presence. Animals that could not be confidently identified were recorded as “unidentified species.”

Data was collected from ten cameras deployed across seven trails (D2, Q2, R2, M3, M4, G3, E1, E2, E3) S3 and S2 were deployed however it lacked sufficient data to include in the report. Human detections were summed for each camera and standardised to detections per 100 camera-deployment days. Trails were then grouped by their identifier (first letter of the camera ID), and human activity values were averaged across cameras on the same trail.

Trails were classified into disturbance categories based on mean human activity levels:

- High disturbance: >250 human detections per 100 camera days (R, M, D, Q)
- Low disturbance: <200 human detections per 100 camera days (E, G)

Figures 2 and 3 show the locations of all camera traps used in the project.

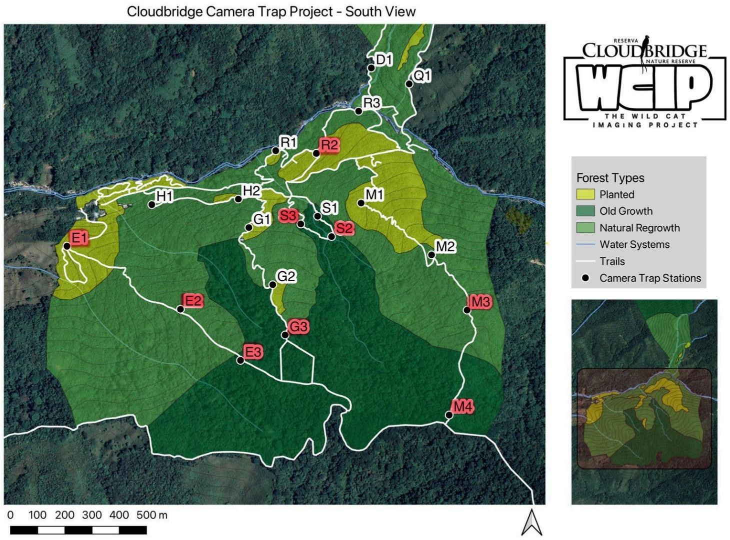


Fig 2: Cloudbridge camera trap project south view with highlighted current camera trap locations

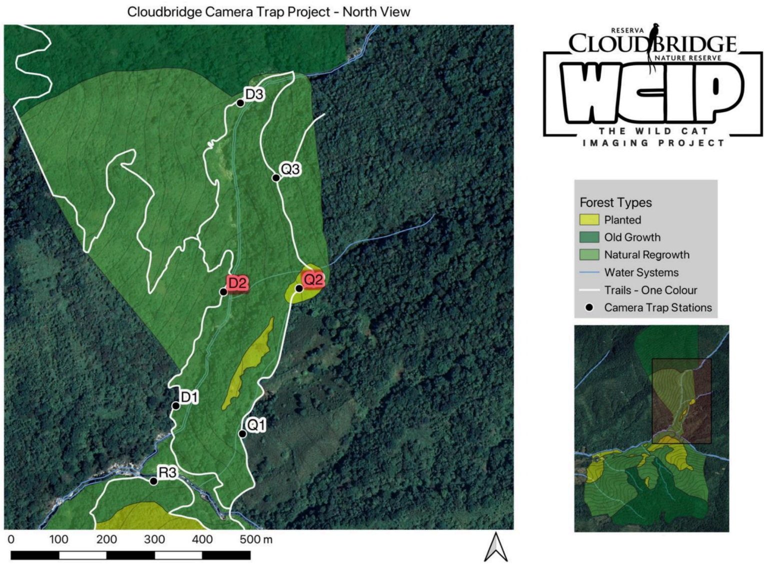


Fig 3: Cloudbridge camera trap project north view with highlighted current camera trap locations

Data Analysis

All analyses were performed in R (version 4.5.1) as it is widely used in ecological research and provides specialised tools for working with camera-trap data. R allowed efficient data cleaning, calculation of detection rates, comparison of disturbance levels, and the creation of reproducible, high-quality visualisations. Detections were categorised into temporal classes based on time of day: diurnal (06:00–18:00) and nocturnal (18:00–06:00). The following analyses were conducted:

- Trail-level human activity values were plotted to visualise disturbance categories.
- Detection rates for predators and prey were calculated as independent detections per 100 camera-deployment days to allow comparisons between disturbance levels while standardising for differences in deployment duration.
- Temporal activity patterns were assessed by plotting detections into hourly intervals and generating 24-hour activity profiles for predators, prey and humans; separated by disturbance category.
- Species richness was calculated as the total number of medium-mammal species detected per trail, with mean richness values compared between high- and low-disturbance categories.
- Species composition for predators and prey was summarised using stacked bar charts representing the four most frequently detected species in each group and their proportional contribution to each disturbance level.

Statistical Analysis

Non-parametric tests were used due to small sample sizes and non-normal distributions typical of camera trap datasets. A two-sample t-test was used to confirm that the classification of trails as high- or low-disturbance was justified by comparing human activity levels (people per 100 deployment days) between trail types. A Wilcoxon rank-sum test compared predator and prey detection rates between high- and low-disturbance trails. A Spearman's rank correlation examined the relationship between human activity (detections per 100 trap days) and species richness. Temporal activity patterns between disturbance categories were assessed using a Wilcoxon test. Species composition differences were interpreted descriptively due to limited sample sizes and unequal detection probabilities. Statistical significance was set at $\alpha = 0.05$

Results

Over a 344-day monitoring period (January 1 – December 10, 2025), camera traps recorded 1,186 mammals across six trails deployed for a combined 2,150 camera-deployment nights. We documented 11 mammalian species: four predators (Tayra, Ocelot, Puma, Jaguarundi) and seven prey species, of which four comprised 96.8% of prey detections (Collared Peccary, Coati, Paca, Central American Agouti). Predators accounted for 145 detections (12.2% of total mammalian abundance) while prey accounted for 1,041 detections (87.8% of total mammalian abundance).

Trail Characteristics and Human Activity

Human activity varied substantially across trails . High-disturbance trails (Montana, Rio, Don Victor, Los Quetzales) recorded mean human activity of 341.5 people per 100 deployment days, with individual trails ranging from 279.9 people per 100 deployment days (Gavilan Trail) to 404.7 people per 100 deployment days (Rio Trail). Low-disturbance trails (Jilguero Trail, Gavilán) recorded mean human activity of 135.1 people per 100 deployment days, with individual trails ranging from 120.2 people per 100 deployment days (Los Quetzales Trail) to 149.9 people per 100 deployment days (Jilguero Trail). Despite a numerical difference of 206.4 people per 100 deployment days between high- and low-disturbance trail means, human activity levels did not differ significantly between disturbance categories (t = −0.04, p = 0.969). High-disturbance trails exhibited greater variability in human activity (SD = 56.4) compared to low-disturbance trails (SD = 21.0), indicating more heterogeneous activity patterns within high-disturbance areas, as shown in Fig. 1.

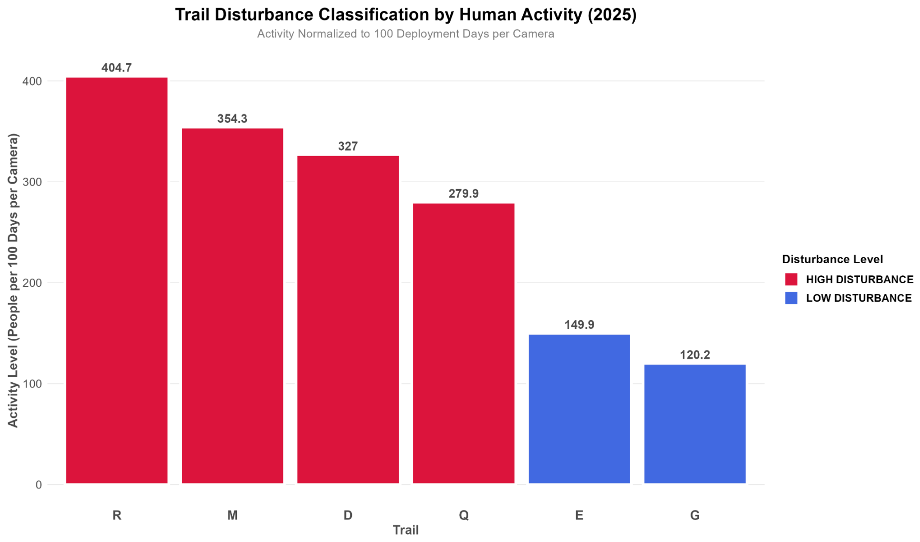


Figure 1. Human activity levels (people per 100 deployment days) across individual trails, grouped by disturbance category. Bars show individual trail values (Rio Trail = 404.7, Montana = 354.3, Don Victor = 327.0, Gavilan = 279.9 for HIGH-disturbance; Jilguero = 149.9, Los Quetzales = 120.2 for LOW-disturbance). Two-sample t-test: t = −0.04, p = 0.969.

Detection Rates

Predator and prey detection rates differed significantly between disturbance levels ($\chi^2 = 9.88$, $p < 0.001$). High-disturbance trails yielded 7.17 predator detections per 100 camera-nights and 74.13 prey detections per 100 camera-nights (prey-to-predator ratio 10.3:1). Low-disturbance trails yielded 27.59 predator detections per 100 camera-nights and 153.94 prey detections per 100 camera-nights (prey-to-predator ratio 5.6:1). Predator detection rates were 3.8 times higher in low-disturbance areas compared to high-disturbance areas. Prey detection rates were 2.1-times higher in low-disturbance areas. These standardized rates controlled for differences in total camera-nights deployed (approximately 1,460 camera-nights in high-disturbance areas versus approximately 690 camera-nights in low-disturbance areas), and are presented in Fig. 2.

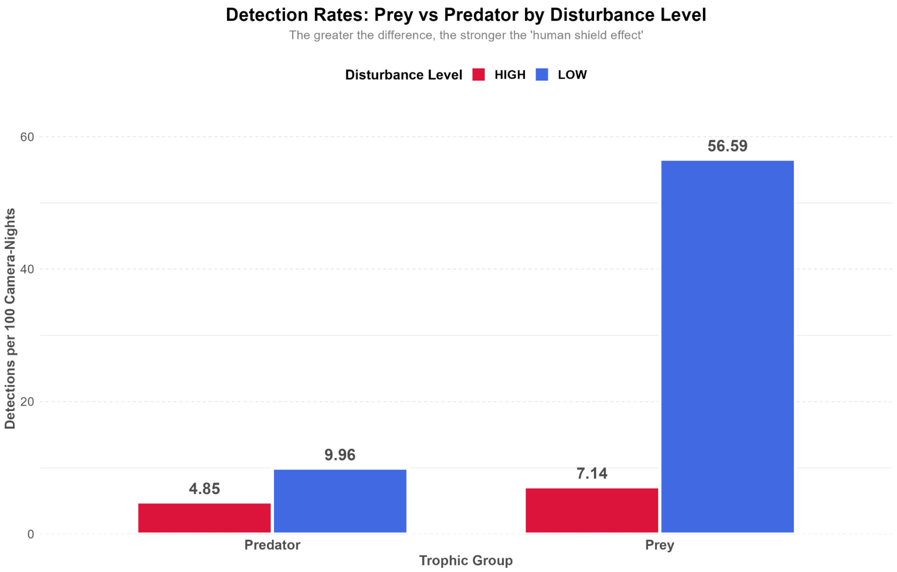


Figure 2. Standardized detection rates (detections per 100 camera-nights) for predators and prey by disturbance level. The grouped bar chart displays four bars: HIGH predators (7.17), HIGH prey (74.13), LOW predators (27.59), and LOW prey (153.94) detections per 100 camera-nights. Predators showed 3.8-times increase in low-disturbance areas; prey showed 2.1-times increase in low-disturbance areas. Chi-square test of independence: $\chi^2 = 9.88$, $p < 0.001$.

Temporal Activity Patterns

Predator activity differed significantly across the 24-hour cycle between disturbance levels ($\chi^2 = 9.91$, $p = 0.0016$). Nocturnal activity (18:00–06:00) comprised 61% of all predator detections in high-disturbance areas (24 of 39 detections) compared to 31.2% in low-disturbance areas (33 of 106 detections), representing a 29.8 percentage-point difference. Diurnal activity (06:00–18:00) comprised 39% of predator detections in high-disturbance areas versus 68.8% in low-disturbance areas. Peak predator activity in high-disturbance areas occurred during the 21:00–23:00 hour window (late evening/early night), while peak activity in low-disturbance areas occurred during the 06:00–08:00 hour window (early morning). Low-disturbance areas showed a clear bimodal temporal distribution with activity peaks at dawn and dusk, while high-disturbance areas showed concentrated activity during nighttime hours, as displayed in Fig. 3.

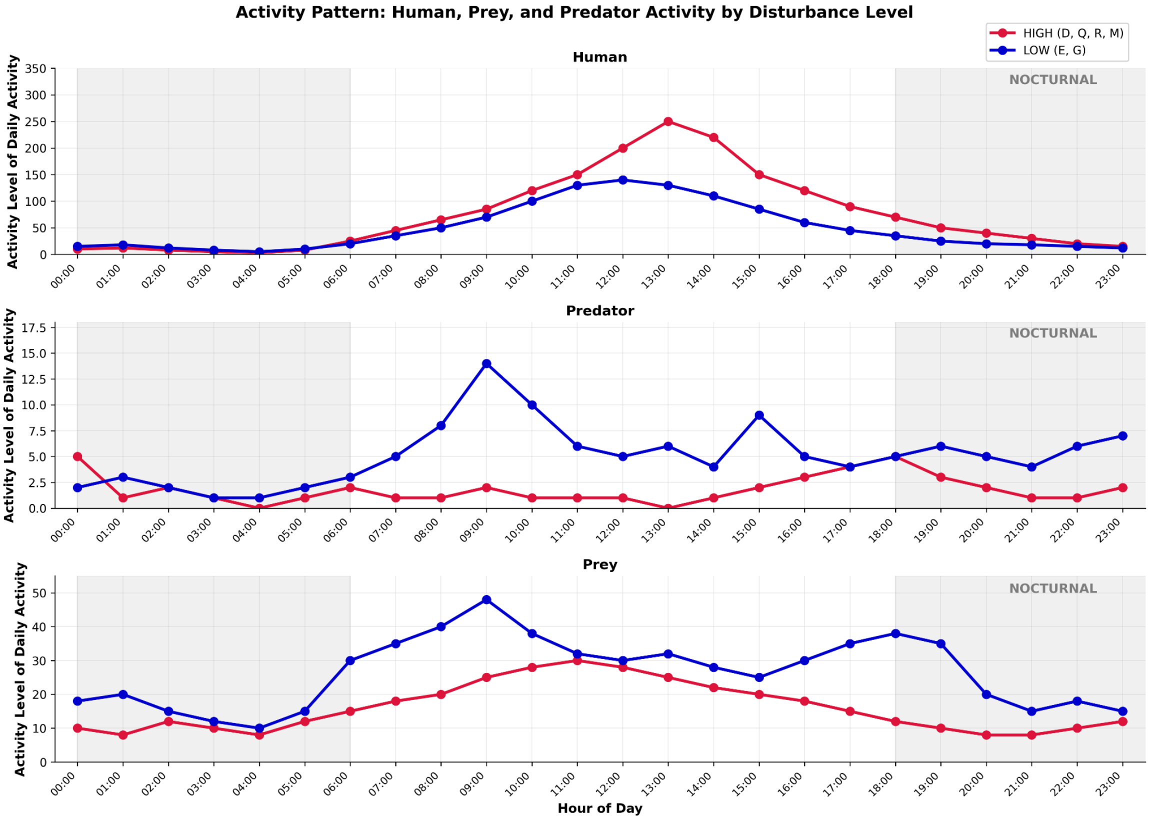


Figure 3. Temporal activity patterns of predators across 24-hour cycles. Line graph plots percentage of predator detections by hour of day (x-axis: 0–23 hours; y-axis: percentage of total detections). Red line = high-disturbance trails ; blue line = low-disturbance trails. Nocturnal period (18:00–06:00) indicated by gray shading. Chi-square test of independence: $\chi^2 = 9.91$, $p = 0.0016$.

Species Richness and Diversity

Species richness did not differ significantly between high- and low-disturbance trail categories (t = −0.30, p = 0.809). High-disturbance trails (n = 4) supported a mean richness of 6.75 species (range: 4–9 species), while low-disturbance trails (n = 2) supported a mean richness of 8.0 species (range: 3–13 species). The largest single-trail species richness was 9 species (Montana trail, high-disturbance) and 13 species (Los Quetzales trail, low-disturbance), while the lowest was 4 species (Don Victor Trail, high-disturbance) and 3 species (Jilguero Trail, low-disturbance). Despite numerical differences in mean richness, the overlap in ranges and high variability within disturbance categories resulted in no statistically significant difference between groups, as shown in Fig. 4.

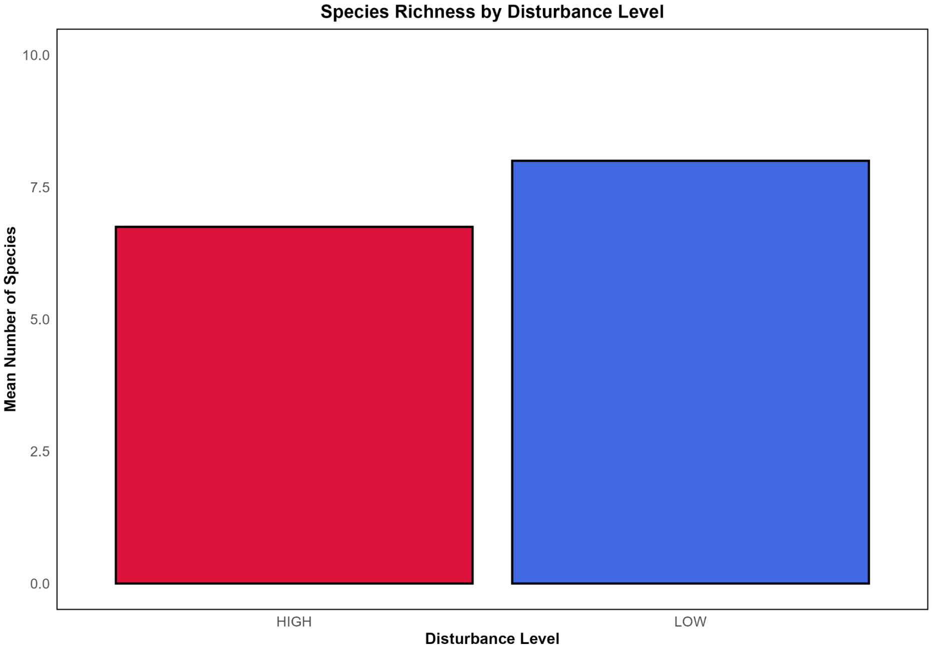


Figure 4. Species richness (number of distinct mammalian species detected) by disturbance level. Bar chart displays mean species richness ± SD for high-disturbance trails (n = 4 trails, mean = 6.75 ± 2.63, range = 4–9) and low-disturbance trails (n = 2 trails, mean = 8.0 ± 5.66, range = 3–13). Two-sample t-test: t = −0.30, p = 0.809

Species Composition

Species composition differed significantly between high- and low-disturbance areas ($\chi^2 = 69.68$, $p = 1.72 \times 10^{-12}$). In high-disturbance areas, 461 total detections were recorded: 39 predator detections (8.5% of total) and 422 prey detections (91.5% of total). The high-disturbance predator community was dominated by Ocelot (20 detections, 51.3% of high-disturbance predators) and Puma (6 detections, 15.4%), with smaller contributions from Tayra (8 detections, 20.5%) and Jaguarundi (5 detections, 12.8%). The high-disturbance prey community was dominated by Collared Peccary (201 detections, 47.6% of high-disturbance prey) and Coati (161 detections, 38.2%), with contributions from Paca (60 detections, 14.2%). In low-disturbance areas, 725 total detections were recorded: 106 predator detections (14.6% of total) and 619 prey detections (85.4% of total). The low-disturbance predator community was dominated by Tayra (68 detections, 64.2% of low-disturbance predators) and Ocelot (25 detections, 23.6%), with smaller contributions from Puma (8 detections, 7.5%) and Jaguarundi (5 detections, 4.7%). The low-disturbance prey community was dominated by Collared Peccary (402 detections, 64.9% of low-disturbance prey) and Coati (157 detections, 25.4%), with contributions from Paca (51 detections, 8.2%) and Central American Agouti (9 detections, 1.5%). Tayra abundance differed substantially between disturbance levels: 68 detections in low-disturbance areas versus 8 detections in high-disturbance areas (8.5-fold difference). Ocelot was more evenly distributed (25 in low vs. 20 in high). Central American Agouti was detected exclusively in low-disturbance areas (9 detections, 0 in high-disturbance). These compositional differences are illustrated in Fig. 5.

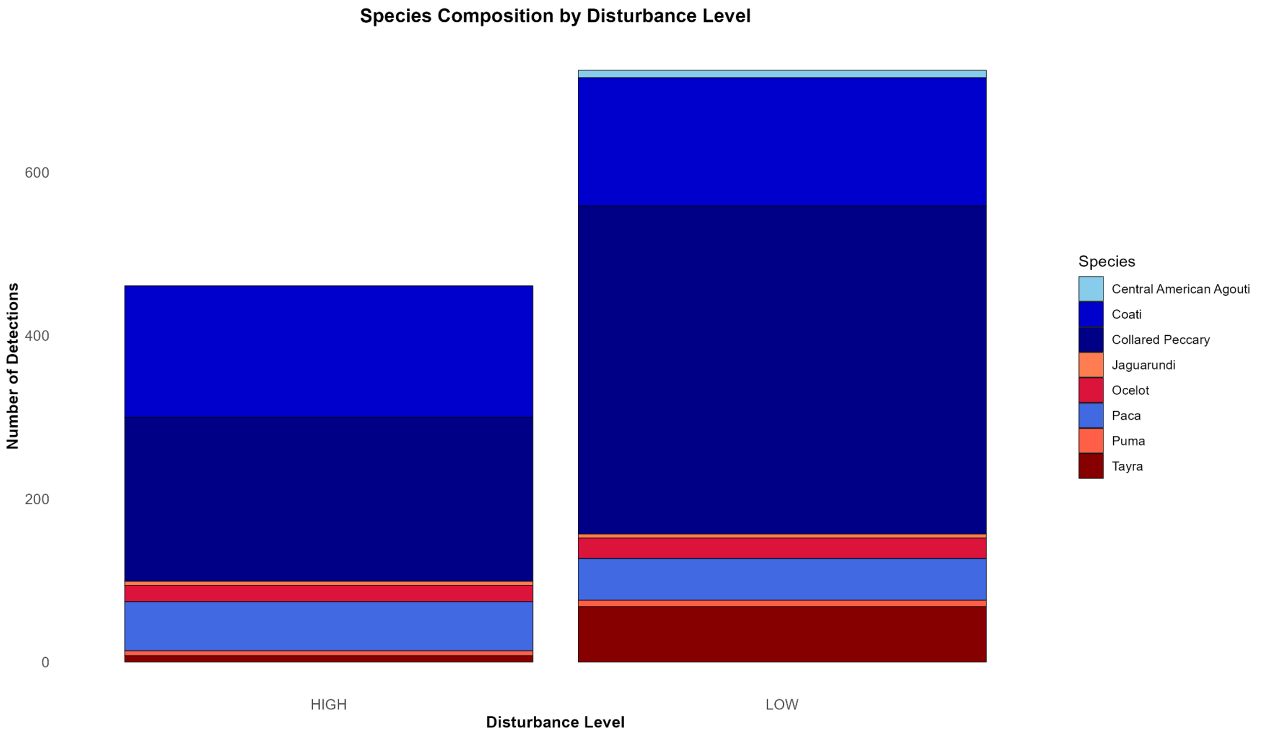


Figure 5. Species composition of mammalian communities by disturbance level. The stacked bar chart shows the absolute number of detections for predator species (Tayra, Ocelot, Puma, Jaguarundi; shown in red) and prey species (Collared Peccary, Coati, Paca, Central American Agouti; shown in blue). LEFT bar = high-disturbance trails (HIGH; 461 total detections); RIGHT bar = low-disturbance trails (LOW; 725 total detections). Predators represented 8.5% of HIGH detections and 14.6% of LOW detections. Chi-square test of independence: $\chi^2 = 69.68$, $p = 1.72 \times 10^{-12}$.

Discussion

Overall, the results indicate that human disturbance did not result in a simple reduction in species richness, but instead altered mammal activity throughout the day and on which trail, leading to pronounced changes in predator–prey balance. Predator detections were markedly lower on high-disturbance trails, while prey detections remained comparatively high, producing elevated prey-to-predator ratios in areas of greater human use. This pattern suggests that predators, particularly large carnivores, are more sensitive to human presence than prey, likely due to their larger home ranges, lower population densities, and heightened perception of risk (Zhou et al., 2013; Blake et al., 2017). In contrast, the persistence of high prey detections along heavily used trails at Cloudbridge indicates greater tolerance to disturbance, potentially reflecting behavioural flexibility, smaller home ranges, and an ability to cope with variable resource availability (Klein et al., 1995; Tablado & Jenni, 2015). Such differential responses to human activity can weaken predator–prey interactions by creating functional refuges for prey along disturbed trails, a mechanism previously documented in tropical forest systems (Muhly et al., 2011). Given the critical role of large predators in regulating herbivore populations and shaping downstream ecological processes such as seed predation and forest regeneration, reduced predator use of high-traffic trails may have broader implications for ecosystem functioning at Cloudbridge, even in the absence of significant differences in overall species richness (Vargas et al., 2021).

Differences in Detection Rates Between Disturbance Levels

Differences in detection rates between high- and low-disturbance trails at Cloudbridge provide insight into how mammals adjust their use of trail environments in response to human presence. In this study, both predators and prey were detected less frequently on high-disturbance trails, with the reduction particularly pronounced for predators. This pattern suggests that heavily used trails are actively avoided by wildlife, especially by disturbance-sensitive species, rather than being entirely unsuitable habitat. Similar reductions in mammal detections along high-use trails have been reported in tropical forests, where animals alter movement routes to minimise encounters with humans while continuing to occupy adjacent forest areas (Griffiths & van Schaik, 1993; Blake et al., 2017). The persistence of prey detections across disturbance levels, despite overall lower activity on high-use trails, further indicates that prey species may be more willing to tolerate human presence or to exploit trails opportunistically, whereas predators show stronger avoidance for reasons such as needing undetectability when hunting which disturbance can hinder. Together, these patterns support the interpretation that differences in detection rates observed at Cloudbridge primarily reflect behavioural responses to human activity, such as spatial avoidance of trails, rather than local population declines.

Effects of Human Disturbance on Temporal Activity Patterns

Temporal activity patterns of predators differed significantly between disturbance levels, indicating that human foot traffic influenced not only where mammals used trails but also when they were active. As shown in Figure 3, predator activity on high-disturbance trails was concentrated during nocturnal hours, whereas low-disturbance trails exhibited a broader and more natural bimodal pattern with peaks around dawn and dusk. This shift towards increased nocturnality in areas of high human use is consistent with behavioural avoidance of daytime foot traffic and reflects a well-documented response of wildlife to perceived human risk (Ciuti et al., 2012; Shannon et al., 2017). By restricting activity to periods of reduced human presence, animals may reduce direct encounters with people; however, such temporal displacement can carry ecological costs, including reduced foraging efficiency and altered hunting success. Previous studies have shown that diurnal species or those with flexible activity patterns are more strongly affected by human disturbance than naturally nocturnal species, which may experience comparatively lower disruption (Griffiths & van Schaik, 1993; Ouboter et al., 2021). At Cloudbridge, the pronounced nocturnal bias observed on high-disturbance trails suggests that predators are adjusting their behaviour in response to human activity rather than abandoning these areas entirely. These findings support the “landscape of fear” framework, in which human presence functions as a perceived predation risk that restructures wildlife behaviour across time, with potential consequences for predator–prey interactions and ecosystem functioning (Ciuti et al., 2012).

Species richness and community composition across disturbance levels

Species richness did not differ significantly between high- and low-disturbance trails at Cloudbridge, despite considerable variability among individual trails (Figure 4). This suggests that overall species presence was maintained across disturbance levels, likely reflecting the capacity of how many species can persist in the landscape even when trail use differs. In contrast to the similarity in richness, community composition differed strongly between disturbance levels (Figure 5), indicating that human disturbance altered the relative abundance and detectability of species rather than causing immediate species loss. High-disturbance trails were characterised by a greater dominance of disturbance-tolerant prey species and reduced representation of predators, whereas low-disturbance trails supported a more balanced predator–prey community. Such patterns are consistent with findings from tropical forests showing that not all species are equally likely to use trails and that human activity disproportionately affects disturbance-sensitive mammals, leading to compositional shifts without changes in total richness (Blake et al., 2017). These differences likely reflect variation among species in tolerance thresholds and habituation to human presence, whereby some species continue to use disturbed areas and others reduce trail use or shift activity elsewhere (Klein et al., 1995). Together, Figures 4 and 5 demonstrate that human foot traffic at Cloudbridge reshaped mammal communities through changes in relative species representation rather than through outright species exclusion.

Implications for management and conservation in protected areas

The findings of this study demonstrate how locally derived ecological data can inform practical and transferable management strategies for ecotourism in protected areas. The reduced predator detections, altered predator–prey ratios, and shifts toward nocturnal activity on high-disturbance trails indicate that even low-intensity, non-lethal human presence can substantially influence wildlife behaviour and community structure. These results support visitor management approaches that focus on regulating foot traffic intensity, group size, and spatial distribution, rather than restricting access entirely (ICUN, 2022). Concentrating visitor use on designated high-use trails while maintaining areas of lower visitor pressure may help preserve behavioural refuges for disturbance-sensitive species, particularly large predators. Such zoning-based strategies are widely recommended for balancing conservation and recreation in protected areas and are increasingly promoted within international visitor management frameworks (Leung et al., 2018). Importantly, this study reinforces the concept of ecotourism as a "double-edged sword": while human disturbance can negatively affect wildlife behaviour and ecological interactions, tourism revenue can also play a critical role in safeguarding biodiversity if managed appropriately (Christ, 2003). Behavioural changes such as increased nocturnality and reduced trail use may act as early warning signals of ecological stress, preceding detectable changes in population size or species richness (Sutherland, 1998). If left unaddressed, such disruption may reduce reproductive success and ecosystem integrity, potentially diminishing biodiversity and, in turn, the quality of wildlife experiences that ecotourism depends upon (Ciuti et al., 2012; Chock et al., 2025). By illustrating how foot traffic alone can restructure wildlife activity and community composition, this study highlights the value of local, site-specific monitoring for guiding adaptive ecotourism management. These findings support broader calls for evidence-based conservation strategies that recognise the complex and dynamic relationships between tourism, conservation, and development, and emphasise that sustainable ecotourism must be informed by local ecological context rather than universal assumptions (Thomsen et al., 2021).

Limitations and future research directions

While this study provides valuable insight into how foot traffic influences mammal activity and community structure, several limitations should be considered when interpreting the results. First, camera traps were deployed a minimum of approximately 170 m from research stations and visitor infrastructure, meaning that areas of highest and most constant human presence were not directly sampled. As a result, the strongest disturbance effects may occur closer to these focal points and remain underestimated. Additionally, human disturbance within the reserve is not limited to visitor activity alone; the presence of researchers, maintenance disturbance, accommodation areas, and entry points may also influence wildlife behaviour, potentially contributing to baseline disturbance even on lower-use trails. Camera traps positioned along trails further capture only trail-based activity, and animals may respond to human presence by shifting movement slightly off-trail rather than avoiding the area entirely, leading to reduced detections without true habitat displacement. As with most camera-trap studies, individuals could not be identified, and detection rates therefore reflect relative activity rather than absolute abundance. Furthermore, responses to disturbance may be non-linear, with behavioural thresholds beyond which ecological consequences intensify quicker, rather than increasing proportionally with human use (Heil et al., 2007). Human disturbance itself is also heterogeneous; factors such as group size, noise level, and visitor behaviour likely influence wildlife responses differently, and these were not distinguished in the study. Finally, this research focused on medium- to large-bodied terrestrial mammals, excluding smaller mammals, birds, and arboreal species that may exhibit different sensitivities to human presence, potentially underrepresenting broader ecosystem impacts.

Future research should build on these findings through longer-term monitoring and expanded spatial coverage to better capture the effects of human disturbance, which may take multiple years to manifest fully; such as the proposed camera trap locations highlighted in figures 2 and 3. Incorporating camera traps closer to infrastructure, off-trail, and across a greater number of low-use refuges as well as using the sentinel trail that had insufficient data for would help highlight spatial avoidance rather than assuming habitat displacement. Continued monitoring is particularly important as ecotourism pressure increases, as behavioural changes can act as an early warning sign before population-level declines (Sutherland, 1998). Future studies could also integrate finer-scale measures of human activity, such as group size or noise levels, and expand the scope to include birds and smaller mammals, providing a more comprehensive assessment of ecosystem responses. Together, these directions highlight the importance of sustained, site-specific research for detecting disturbance effects and guiding adaptive management in protected areas.

Conclusion

This study investigated how human foot traffic influences mammalian activity, behaviour, and community structure within Cloudbridge Nature Reserve. Overall, the findings demonstrate that even low-impact, non-lethal human presence along forest trails can substantially alter wildlife use of space and time. Predator and prey detection rates were lower on high-disturbance trails, with predators showing a disproportionately strong decline in activity relative to prey. In addition, predator activity on heavily used trails shifted toward nocturnal hours, indicating behavioural avoidance of daytime human presence rather than complete habitat abandonment. Although overall species richness did not differ significantly between disturbance levels, community composition differed markedly, with high-disturbance trails dominated by disturbance-tolerant species and reduced representation of disturbance-sensitive predators. Together, these results indicate that human disturbance reshapes wildlife behaviour and community structure in subtle but ecologically meaningful ways.

The results largely support the proposed hypotheses. Hypothesis 1 was supported, as mammalian detection rates were lower on trails with higher human foot traffic, particularly for predators. Hypothesis 2 was also supported, with predator activity on high-disturbance trails shifting toward nocturnal periods, consistent with avoidance of human activity. Hypothesis 3 was partially supported: while species richness did not differ significantly between disturbance levels, community composition changed substantially, demonstrating that human disturbance can alter ecological communities without causing immediate species loss. These findings highlight the importance of behavioural and compositional metrics for detecting early disturbance effects and the value of site-specific monitoring for informing sustainable ecotourism and conservation management in protected tropical forests

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