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Short Communication

Arboreal mammal use of canopy walkway bridges in an Amazonian forest with continuous canopy cover

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Abstract

The Amazon Basin is a biodiversity hotspot, with vertically stratified forests fostering complex habitats and high mammal diversity. Although mammals play a critical role in maintaining ecosystem structure, less is known about arboreal mammal activity and habitat use across forest canopy layers. As forest fragmentation increases, understanding how these changes impact arboreal species is essential for effective conservation efforts. Here, we provide a snapshot of canopy walkway use by arboreal mammals in an Amazonian forest with unfragmented canopy cover, providing insight into their spatial and temporal movement patterns across different canopy layers. This study was conducted at the Amazon Conservatory for Tropical Studies, in the Napo-Sucusari Biological Reserve outside Iquitos, Perú. During a three-week survey, we deployed camera traps at multiple heights along a canopy walkway system to monitor arboreal mammal activity. A total of seven mammal species used this canopy walkway system during our study period. Linnaeus's two-toed sloth (*Choloepus didactylus*) and the long-tailed porcupine (*Coendou longicaudatus longicaudatus*) were the most commonly observed species, with several observations of the more reclusive and data-deficient *C. ichillus* also recorded, among other species. Peak activity occurred between 1900 and 2100 h, coinciding with higher temperature and humidity than nighttime averages. Mid-canopy layers (ca. 21 to 27 m above ground) were most frequently used, with decline in use at higher and lower canopy layers. Our findings provide baseline data on arboreal mammal use of canopy walkways in a tropical forest, which may help inform the design of human-created arboreal corridors to connect forest fragments.

Key words: artificial bridges, camera traps, *Coendou ichillus*, forest canopies, habitat connectivity, microclimate, South America, tropical conservation

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Introduction

The Amazon Basin is the world's largest tropical forest (Peres et al. 2010), hosting approximately 5,000 tree species (Wittmann and Junk 2016). Three-quarters of vertebrate species in the Amazon are arboreal or semi-arboreal (Kays and Allison 2001), representing the majority of vertebrate total biomass and diversity (Eisenberg and Thorington 1973). Arboreal vertebrates, particularly mammals, promote plant diversity (Kurten et al. 2015) and affect ecosystem structure

(Klimeš et al. 2012) through dispersal. Understanding the ecology of arboreal species is crucial to their conservation and management strategies (Tobler et al. 2008) and, in turn, the health of Amazonian ecosystems as a whole.

As human-created forest fragmentation continues to alter the Amazon Basin (Lapola et al. 2023), it is crucial to understand how arboreal species are affected by these changes. In particular, arboreal mammal movement through canopies in tropical forests is an area of conservation interest, given their role in dispersal (e.g., Stoner et al. 2007; Brockelman et al. 2022). Conservationists in tropical forests worldwide (Gregory et al. 2022a) have found success in implementing canopy bridges to mitigate forest fragmentation (Wilson et al. 2007), as canopy bridges can successfully promote connectivity for critically endangered species (e.g., Chan et al. 2020) and reduce vehicle collisions and mortality (Flatt et al. 2022).

From the forest floor to the canopy, tropical forest microhabitats vary due to changes in radiation, temperature, vapor pressure, and precipitation (Madigosky 2004); these microhabitat differences, in addition to strata height and connectivity, can influence mammal space use and activity patterns in forests (Abreu and Oliveira 2014; McLean et al. 2016). Over a 24-hour period, arboreal mammal activity in forests likewise varies, with peak activity at nightfall (Bowler et al. 2017; Gregory et al. 2022b). However, compared to forests with continuous canopies, the spatial distributions and activity patterns of arboreal mammals in fragmented forests may differ as they search for suitable microhabitats (Tregidgo et al. 2010).

Increased canopy openness negatively affects arboreal mammal richness (e.g., Cudney-Valenzuela et al. 2023, Whitworth et al. 2019), and human-created canopy bridges can help mitigate effects on arboreal mammals in fragmented forests (e.g., Gregory et al. 2022a). However, the extent to which arboreal species use artificial bridges across different canopy layers, and when they use them, remains poorly understood across diverse Neotropical habitats. The goal of this study is to (1) provide information about arboreal mammal use of artificial canopy walkways and (2) assess how artificial canopy walkway use varies across different canopy layers throughout a diel cycle in a lowland Amazonian forest with continuous canopy cover. How mammals use artificial canopy walkways in a tropical forest with unfragmented canopy can inform the development of best practices for designing conservation bridges in fragmented landscapes.

This study provides a snapshot of mammalian spatial and temporal use of one of the longest artificial canopy walkway bridge systems, spanning multiple forest levels, in the Americas. In this study, we used camera traps to monitor arboreal mammal activity to provide a baseline for understanding mammalian use of artificial bridges in an Amazonian forest. Our study complements previous arboreal camera trap research on canopy bridges in fragmented forests (e.g., Gregory et al. 2022a).

Methods

Through July and August 2022, we deployed four camera traps continuously for 21 days over a canopy height gradient using the Amazon Conservatory for Tropical Studies (ACTS) Canopy Walkway (3.2513°S, 72.9076°W). The ACTS Canopy Walkway is located in the Napo-Sucusari Biological Reserve, northeast of Iquitos, Perú and north of the Napo River (Fig. 1). The canopy walkway system is a series of platforms and bridges (Fig. 2), with platforms ranging from 6 to 36 m above the forest floor built for researcher and visitor use. We placed camera traps at 12.1 m,

Figure 1. Location of the Amazon Conservatory for Tropical Studies (ACTS) Field Station at the Napo-Sucusari Biological Reserve, in northeastern Perú, with black rectangle on inset map showing the enlarged area.

20.8 m, 26.5 m, and 33.5 m above the ground; these camera sites were chosen due to their similar connectivity to nearby vegetation, canopy spacing, and elevation.

We fastened each camera to the nearest tree or beam from the platform, which overlooked a potential wildlife pathway (as determined by connectivity between trees and bridges). We checked the cameras daily to ensure functionality and positioning. At the end of each week, we extracted data from the memory cards and returned them once the media were downloaded. The camera traps we deployed were a Victure HC200 (Shenzhen Dajie Technology Co., Ltd., Shenzhen, GD, China), Moultrie MCG-14007 (Moultrie Inc., Alabaster, AL, USA), and Wildgame Innovations Scrapeline™ SP16B20D18-9 and Mirage™ M18i8W26-9 (Wildgame Innovations, New Roads, LA, USA). We set all camera infrared sensors to high sensitivity, which triggers the camera to capture any change in the infrared radiation being emitted by an object in the camera's field of view; the high sensitivity setting also allowed the camera to capture smaller animals and those that are at a distance. For the first half of the study, each camera was set to capture 15-second videos throughout the 24-hour operation period when triggered. During the second half, cameras were set to capture photographs with three photographs taken per trigger event; the decision to collect photographs in lieu of videos was made to save on memory storage and battery usage of the equipment.

In our analysis, we quantified mammalian walkway use at night, as no daytime observations were recorded. Human use of the walkway was excluded from the study; as human triggered camera traps outside of the sampling period (all were during daytime), we could not explore the effects of human foot traffic on mammalian walkway use. Our night sampling period extended from approximately

Figure 2. The Amazon Conservatory for Tropical Studies Canopy Walkway in the lowland Peruvian Amazon with identified structural components used by arboreal mammals. Photographs by J. Santiago.

sunset (1800 h) to sunrise (0600 h). We classified observations on the walkway system into two components: the walkway bridges and their beams (Fig. 2). Independent events were separated by 30 minutes, as suggested by similar camera trap studies (Pittet and Bennett 2014; Huarcaya et al. 2019; Tanwar et al. 2021). Due to the similar traits of *Coendou bicolor* and *Coendou l. longicaudatus*, camera trap images that did not contain any distinctive identifiers were simply grouped by genus: "*Coendou* sp." Camera trap footage and photographs allowed us to discriminate *Coendou ichillus* and *Coendou bicolor* by their recognizable size and pelage difference: *Coendou ichillus* is smaller, darker, and has a smaller tail and bristle quills (Voss and Da Silva 2001). In addition, multiple species of saki monkey occur in the Amazon basin, differing in minor facial characteristics and pelage; because of this, we grouped saki monkeys by genus (*Pithecia*) in this study. Similarly, we grouped Neotropical spiny rats by family (Echimyidae), as all

twelve species show arboreal tendencies with similar morphological traits. We recorded other species that triggered camera traps but did not interact with the walkway's structural elements (i.e., bats) as "incidental" species, as mammals accessing the canopy walkway were the focus of this study.

Temperature, humidity, and wind speed were collected hourly using Kestrel 5000 Environmental Meters, placed near the forest floor (1 m above ground), mid-canopy (20 m above ground), and in the upper canopy (36 m above ground). We used a linear mixed effect model (*lme4* package; Bates et al. 2015) to test whether environmental conditions varied with canopy strata, with time as a random effect. We used the *emmeans* package (Lenth 2024) to conduct pairwise tests to determine environmental differences between specific canopy layers. All tests were two-tailed, maintained an alpha value of 0.05, and were conducted in R (R Core Team 2023).

Results

All camera traps successfully recorded continuously during the study period, with the exception of the camera at 26.5 m, which was operational for only one week. In total, the camera traps operated for a total of 1,680 camera trap hours (see Suppl. material 1: table S1) and recorded 35 independent mammal observations; both videos and photographs (Fig. 3) were collected.

A total of seven mammal species (Table 1), in addition to incidental mammal observations in flight (chiropterans) were identified. Linnaeus's two-toed sloth (*Choloepus didactylus*) was the most frequently observed species overall, with 14 independent sightings exclusively on the ropes of the walkway bridge, followed by long-tailed porcupines (*Coendou l. longicaudatus*, now a morphotype of *Coendou prehensilis*; Menezes et al. 2021), with 10

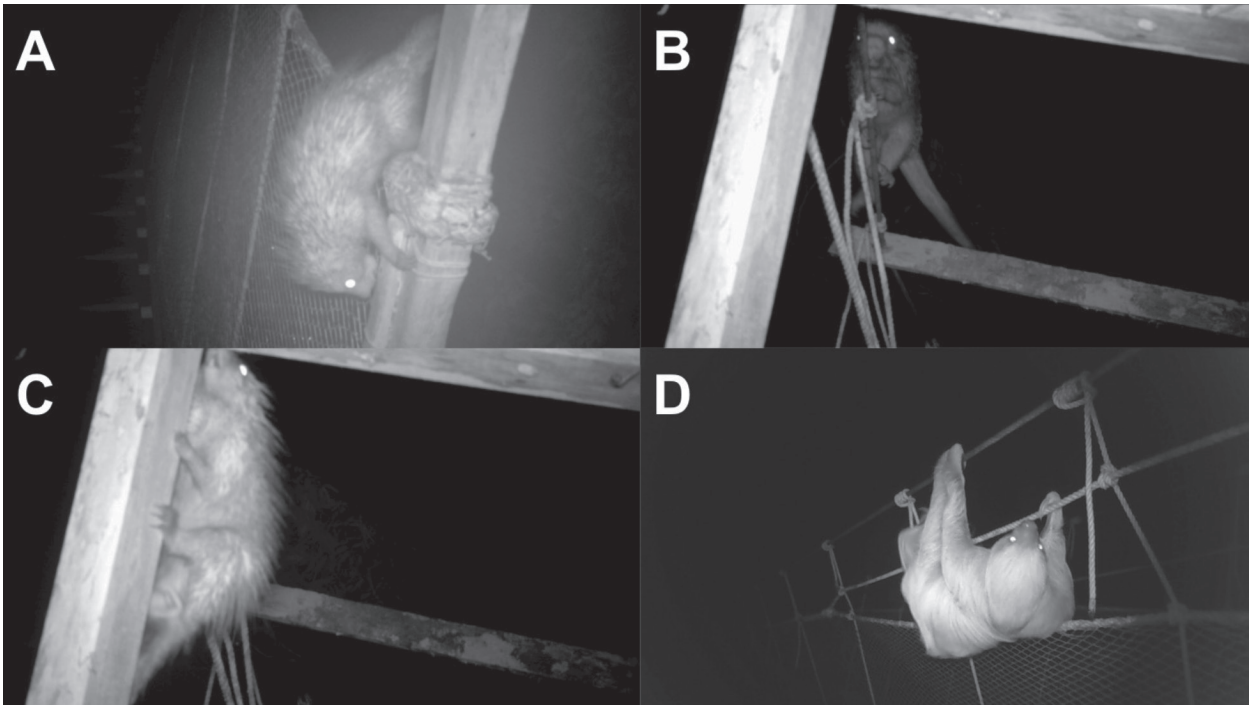

Figure 3. Camera trap images of mammals found during the survey period: **A.** *Coendou bicolor*; **B.** *Coendou l. longicaudatus*; **C.** *Coendou ichillus*; **D.** *Choloepus didactylus*, all recorded on the Amazon Conservatory for Tropical Studies Canopy Walkway. Camera captures by J. Santiago.

Table 1. Species observations at different structural locations and heights (m) on the ACTS Canopy Walkway, shown with their common English and local names, the number of unique observations (N) of each species at each location (Loc.) (in parentheses), and species or genus IUCN conservation status (LC = Least Concern, DD = Data Deficient) and population trajectories.

Observed mammal walkway use and conservation status					
Species	**English Name**	**Local Name**	**Loc.**	**Height (m) and (N)**	**classified observations on**
Choloepus didactylus	Linnaeus's Two-toed Sloth	*pelejo colorado*	Beam, Rope	20.8 m (2) 33.5 m (12)	LC - Decreasing (Chiarello et al. 2022)
Coendou l. longicaudatus	Long-tailed Porcupine	*cashacushillo*	Beam, Rope	20.8 m (5) 33.5 m (5)	LC - Stable (Marinho-Filho and Emmons 2016)
Coendou ichillus	Streaked Dwarf Porcupine	*puercoespín enano rayado*	Beam, Rope	20.8 m (4) 33.5 m (2)	DD (Weksler et al. 2016)
Coendou bicolor	Bicolor-spined Porcupine	*puercoespín bicolor*	Beam, Rope	20.8 m (2) 33.5 m (3)	LC - Trend Unknown (Delgado 2016)
Caluromys lanatus	Brown-eared Woolly Opossum	*zarigüeya lanuda occidental*	Beam	20.8 m (2)	LC - Decreasing (Costa et al. 2021)
Pithecia sp.	Saki Monkey	*saki/huapo negro*	Beam	20.8 m (1)	LC – Decreasing (IUCN 2024)
Echimyidae	Neotropical Spiny Rats	*ratón espinoso*	Beam	20.8 m (1)	-

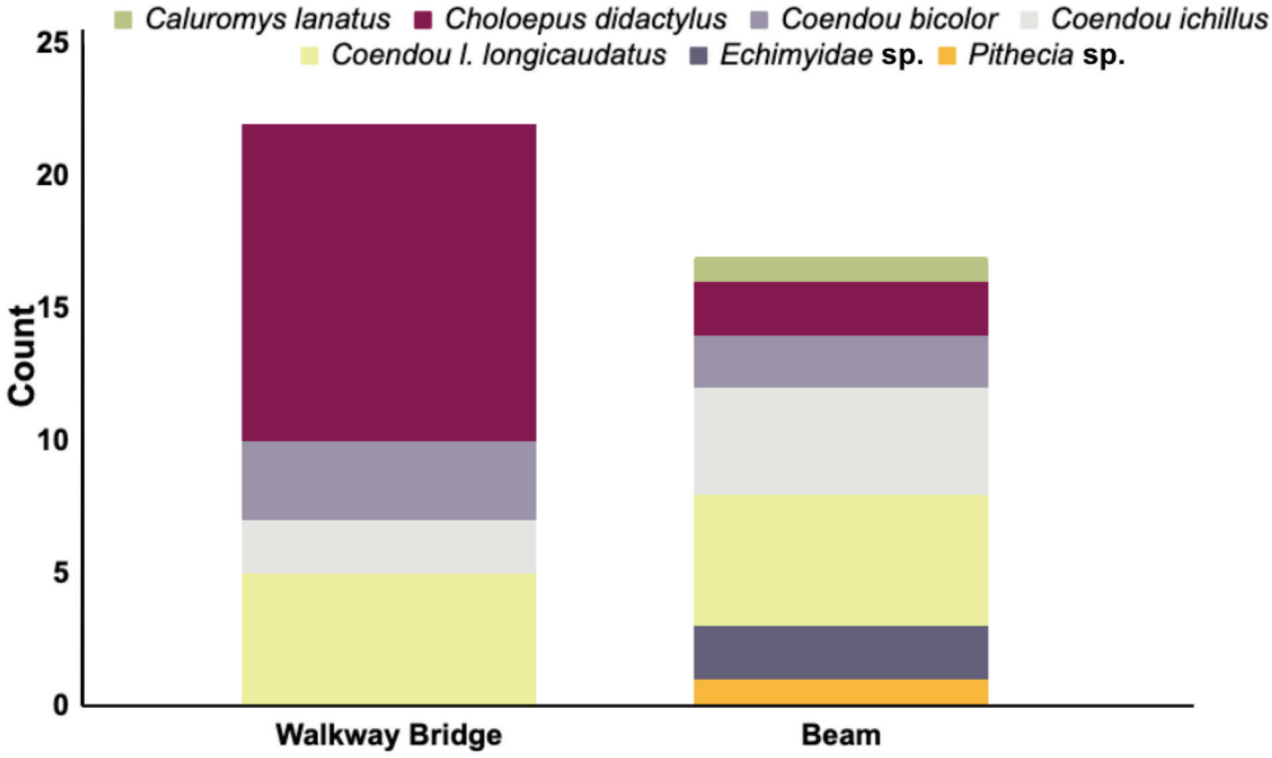

Figure 4. Mammal use of structural components of the canopy walkway (walkway bridges or beams) on the Amazon Conservatory for Tropical Studies Canopy Walkway. Walkway bridges received the greatest overall use, with a greater diversity of mammals observed on the beams than bridges.

independent sightings on both the beams and ropes of the walkway. Of the two walkway components (walkway bridges and beams), the walkway bridge was the most frequently visited, with many of the reported species also using the beams as an access point to the rest of the walkway platform (Fig. 4; Suppl. material 1: table S2).

Most mammal observations occurred mid-canopy (at 20.8 m; Fig. 5, Suppl. material 1: table S3), including Linnaeus's two-toed sloths (*Choloepus didactylus*), long-tailed porcupines (*Coendou l. longicaudatus*) (Suppl. material 1: video S1), streaked dwarf porcupines (*Coendou ichillus*), bicolor-spined porcupines

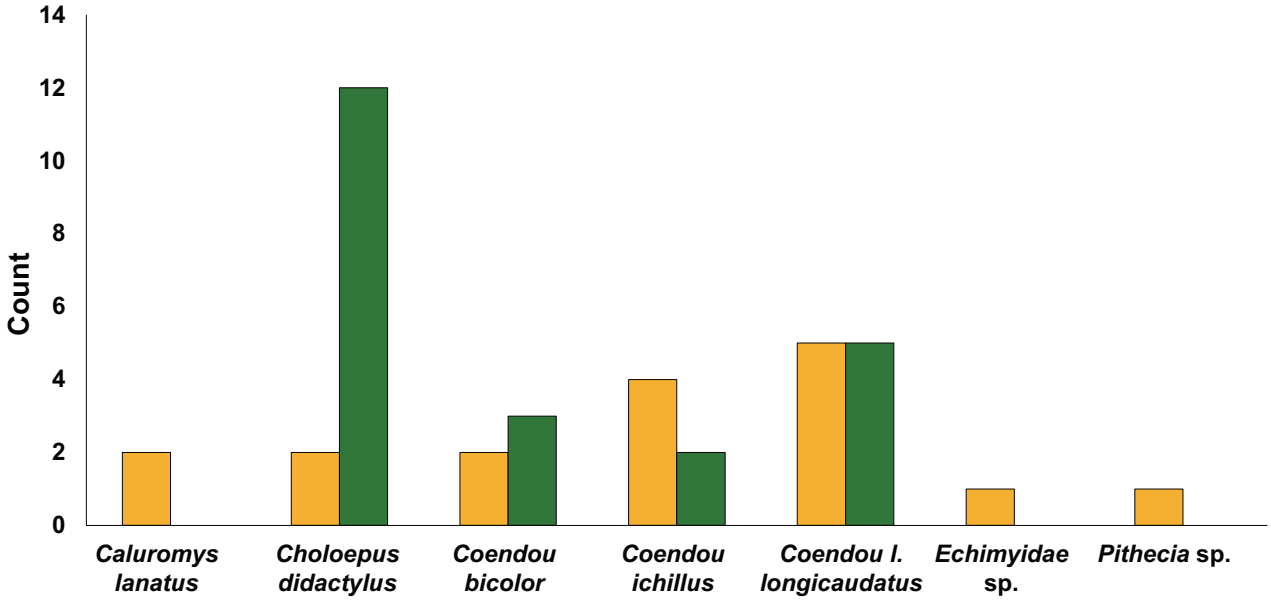

Figure 5. Species observations by height above ground for two camera traps (set at 20.8 m, orange; 33.5 m, green) where mammals were recorded on the Amazon Conservatory for Tropical Studies Canopy Walkway.

Table 2. Pairwise comparisons of three environmental variables (temperature (°C), relative humidity (%), and wind speed (m/s)) measured at the forest floor (1 m above ground, "Floor"), mid-canopy (20 m, "Mid"), and upper canopy (36 m, "Upper"). Mean differences of each pairwise comparison shown, in addition to the *P* values from Tukey post hoc comparisons. Asterisks denote significant differences ($P < 0.05$).

Pairwise comparisons of walkway environmental variables			
Variable	**Pairwise Comparison**	**Difference**	**P**
Temperature	Upper - Mid	0.25	0.023*
	Upper - Floor	0.54	< 0.001*
	Mid - Floor	0.29	0.007*
Humidity	Upper - Mid	-1.13	< 0.001*
	Upper - Floor	-1.74	< 0.001*
	Mid - Floor	-0.62	0.065
Wind Speed	Upper - Mid	0.15	< 0.001*
	Upper - Floor	0.18	< 0.001*
	Mid - Floor	0.03	0.534

(*Coendou bicolor*) (Suppl. material 1: video S2), saki monkey (*Pithecia* sp.), Neotropical spiny rat (Echimyidae), and brown-eared woolly opossum (*Caluromys lanatus*) (Suppl. material 1: video S3), in addition to the incidental chiropteran species. Mammals were next most frequently observed in the upper canopy (at 33.5 m), and no mammals were recorded by the camera trap at 12.1 m. During the study period, environmental conditions significantly varied by canopy layer (Table 2): temperature ($\chi^2_2 = 35.785$, $P < 0.001$; Fig. 6a) and wind speed ($\chi^2_2 = 64.143$, $P < 0.001$; Fig. 6b) were highest in the upper canopy and decreased toward the forest floor, whereas humidity ($\chi^2_2 = 43.569$, $P < 0.001$; Fig. 6c) was greatest at the forest floor and decreased toward the canopy.

Most mammal activity was first recorded between 1900 and 2100 h and concluded by 0200 h, though *Choloepus didactylus* continued to be active until 0400 h (Fig. 7). Mammal diversity peaked between 2000 and 2200 h; during this period, mean temperature was 24.3 °C ± 0.09 and mean humidity was 84.6% ± 0.73, both significantly higher than the mean at nighttime (1800 to

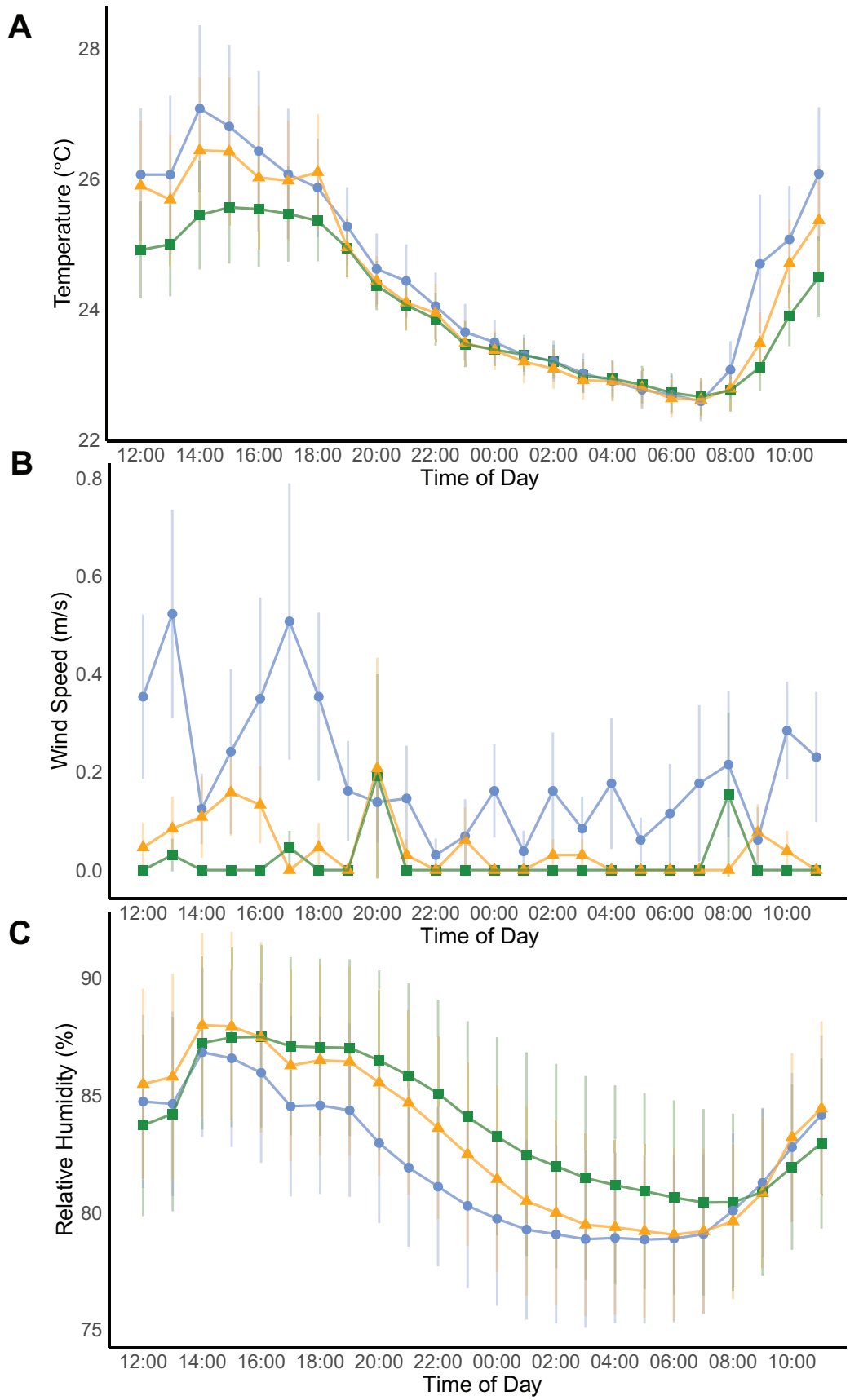

Figure 6. Mean **A.** Temperature (°C); **B.** Wind speed (m/s), and **C.** Relative humidity (%), with error bars representing ± 1 SE, at three canopy strata: upper canopy (36 m above ground, blue circles), mid canopy (20 m, gold triangles), and forest floor (1 m, green squares), at the Amazon Conservatory for Tropical Studies Canopy Walkway.

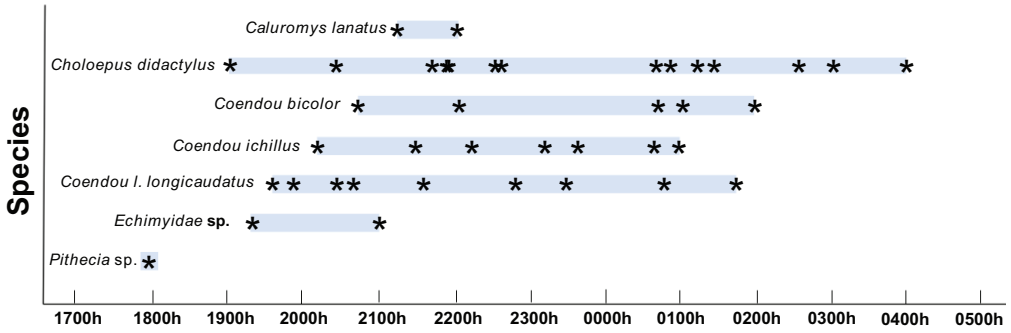

Figure 7. Mammal observations (with individual observations indicated by asterisks) throughout the duration of the sampling period (1800 h to 0600 h) on the Amazon Conservatory for Tropical Studies Canopy Walkway. Blue bars indicate the time range of observations per mammal or group.

0600 h) (temperature: 23.7 °C ± 0.13; $t = 3.74$, $P < 0.001$; humidity: 82.0% ± 0.34; $t = 3.26$, $P = 0.013$). Wind speeds during the period of peak mammal observations did not differ from mean nighttime wind speed (0.12 m/s ± 0.03 versus 0.07 m/s ± 0.01, respectively; $t = 1.46$, $P = 0.193$).

Discussion

This study provides a snapshot of arboreal mammal use of an artificial canopy walkway system in a tropical forest with continuous canopy cover in the northeastern Peruvian Amazon. Our findings demonstrate that many arboreal mammal species, even cryptic and reclusive species like *Coendou ichillus*, actively use human-made canopy structures, even within a continuous, non-fragmented forest. Most mammals used the rope bridges of the walkway; although bridge floor planks were available, no usage was observed, and camera angles likely would have captured it if it occurred. Most mammals recorded used the walkway system for movement, with little evidence of foraging (though porcupines chewed on walkway beams). This suggests that the canopy walkway is used primarily by mammals as movement corridors, rather than foraging hotspots.

Mammal activity patterns, beginning around 1900 h and peaking between 2000 and 2200 h, correspond to similar findings by other studies of arboreal mammal behavior on natural canopy bridges (Gregory et al. 2015; Gregory et al. 2022b). In the larger study conducted by Gregory et al. (2022b), 5,000 observed individual events were recorded, accounting for 27 arboreal mammal species, with 87.4% of events at natural canopy bridges occurring between 1800 and 0600 hr. In our study, we found that mammal activity peaked while temperature and humidity were relatively high, suggesting that these conditions may either be favorable for arboreal mammal foraging and social activities, or correlated with some other aspect of their environment or biology, perhaps related to increased foraging motivation during their first few hours of activity. These findings also suggest that efforts could be taken to minimize disturbance to artificial canopy bridges in fragmented forests during these peak movement hours and (potentially) while temperature and humidity remain relatively high.

We found that the mid-canopy (ca. 21 to 27 m) was the most heavily used canopy layer, with activity decreasing at lower (less than 20 m) and higher (above 27 m) layers, possibly reflecting a preference for lower-risk, more concealed pathways through the canopy (Ferrari 2009). The upper canopy was

characterized by higher temperatures and wind speeds, conditions that may be less favorable for some species, and consistent with the trends for small mammals observed by Basham et al. (2023). These microclimatic differences are likely to influence the activity patterns and habitat selection of arboreal mammals, highlighting the need for canopy connectivity via walkway design that accounts for both environmental gradients and species-specific requirements.

A particular species of note that was observed in this study is the data-deficient streaked dwarf porcupine (*Coendou ichillus*), which was only relatively recently recognized by Western science when researchers noted distinctive morphological traits on a specimen collected from von Baumann-Roosevelt's 1936 Expedition in Ecuador (Voss and Da Silva 2001); the first live documentation of *C. ichillus* was reported in 2013 (Gregory et al. 2015). Previous work identified seasonal variation in the activity of *C. ichillus* (Gregory et al. 2022b) and similar activity times (between 1800 and 0500 h, with activity peaking at 2000 h) as we identified in our study (2000 to 0100 h). Erethizontids, to which *C. ichillus* belongs, are characterized by their reclusive cryptic behavior which contributes to the limited available data (Menezes et al. 2020); observing their activity periods could provide additional insights into their behavior, leading to appropriate conservation measures and outcomes.

The role of anthropogenic structures in promoting connectivity among forest fragments is of particular interest in conservation biology (e.g., Soanes et al. 2015, Weston et al. 2011, Yap et al. 2022). Given the increasing fragmentation of tropical forests, the use of these structures offers a promising and effective solution to maintain natural mammal population movements (e.g., Gregory et al. 2017, Chan et al. 2020, Birot et al. 2020). Understanding how mammals use artificial canopy walkways in a continuous forest may enable future planning of more naturally structured or accessible artificial bridges.

Conclusion

Here, we provide a snapshot of how arboreal mammals in the Amazon Basin use an artificial canopy walkway system. This study is one of the first to measure mammal use of human-made canopy structures in a tropical forest with a continuous canopy, and we provide baseline data on species visitations and their spatial and temporal patterns of use. Greater understanding of how arboreal mammals interact with these structures in forests could inform the design and implementation of wildlife bridges in fragmented forests to mitigate the effects of habitat fragmentation on canopy species. Much remains to be explored regarding the long-term ecological impacts of these structures on populations and their role in supporting biodiversity. Our findings suggest that artificial canopy walkways are used by many nocturnal mammal species, although further research is needed to assess their effectiveness more broadly in the Amazon and across various levels of forest fragmentation.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

No funding was reported.

Author contributions

J.S. designed the study and developed the methodology, with guidance from L.S. J.S. deployed and maintained camera traps and compiled resulting data, and L.S. collected environmental data and performed statistical analyses. J.S. and L.S. wrote the manuscript and interpreted the results.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary information

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