

## Brief Report

# Arboreal wildlife bridges in the tropical rainforest of Costa Rica's Osa Peninsula

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**Abstract** – Linear infrastructures, especially roads, affect the integrity of natural habitats worldwide. Roads act as a barrier to animal movement, cause mortality, decrease gene flow and increase the probability of local extinctions, particularly for arboreal species. Arboreal wildlife bridges increase connectivity of fragmented forests by allowing wildlife to safely traverse roads. However, the majority of studies about such infrastructure are from Australia, while information on lowland tropical rainforest systems in Meso and South America remains sparse. To better facilitate potential movement between forest areas for the arboreal wildlife community of Costa Rica's Osa Peninsula, we installed and monitored the early use of 12 arboreal wildlife bridges of three different designs (single rope, double rope, and ladder bridges). We show that during the first 6 months of monitoring via camera traps, 7 of the 12 bridges were used, and all bridge designs experienced wildlife activity (mammals crossing and birds perching). A total of 5 mammal species crossing and 3 bird species perching were observed. In addition to preliminary results of wildlife usage, we also provide technical information on the bridge site selection process, bridge construction steps, installation time, and overall associated costs of each design. Finally, we highlight aspects to be tested in the future, including additional bridge designs, monitoring approaches, and the use of wildlife attractants.

**Resumen** – Las infraestructuras lineales, especialmente las carreteras, afectan la integridad de los hábitats naturales en todo el mundo. Las carreteras actúan como una barrera para el movimiento de animales, causan mortalidad y disminución de la diversidad genética y aumento en la probabilidad de extinción local, particularmente para las especies arbóreas. Los puentes arbóreos para fauna silvestre aumentan la conectividad de los bosques fragmentados y permiten el cruce de carreteras de fauna arbórea de manera segura. Sin embargo, la mayoría de los estudios hasta la fecha sobre estas infraestructuras provienen de áreas tropicales húmedas de Australia; mientras que, la información sobre los sistemas de bosques lluviosos tropicales de tierras bajas en

Meso y América del Sur sigue siendo escasa. Con el fin de facilitar el potencial movimiento entre parches de bosque de la comunidad de fauna arbórea de la Península de Osa de Costa Rica, instalamos y monitoreamos el uso temprano de 12 puentes de fauna de tres diseños diferentes (cuerda simple, cuerda doble, y puente de escalera). Encontramos que durante los primeros 6 meses de monitoreo utilizando cámaras trampa, 7 de 12 puentes fueron utilizados, y todos los diseños probados presentaron actividad por parte de la vida silvestre. En total cruzaron 5 especies de mamíferos y 3 especies de aves los utilizaron para perchearse. Además de nuestros resultados preliminares de uso por parte de la vida silvestre, también presentamos información técnica respecto al proceso de selección de sitios, los pasos para la construcción de puentes, el tiempo de instalación, y costos totales de cada uno de los diseños utilizados. Finalmente, destacamos futuros aspectos que se pondrán a prueba con respecto al diseño, monitoreo y uso de atrayentes de fauna. Finalmente, destacamos futuros aspectos que se pondrán a prueba con respecto al diseño, monitoreo y uso de atrayentes de fauna.

**Keywords** – arboreal bridges, arboreal mammals, canopy bridge, connectivity, forest fragmentation, roads, wildlife crossings.

## Introduction

Slicing through ecosystems, linear infrastructures – such as roads – affect the integrity of habitats worldwide (Laurance et al., 2009; Freitas et al., 2010). A barrier to animal movements and a cause of mortality, roads decrease gene flow and increase the probability of local extinctions, especially for arboreal species (Wilson et al., 2007; Yokochi et al., 2015; Asensio et al., 2017; Srbek-Araujo et al., 2018). Arboreal wildlife bridges, however, have proven a successful tool to overcome this conservation challenge. Artificial and natural arboreal bridges increase connectivity of fragmented forests, allowing wildlife to safely traverse roads and power lines, providing an effective solution to avoid fatal traffic collisions or electrocutions, and increasing the movement of isolated arboreal wildlife populations (Teixeira et al., 2013; Balbuena et al., 2019; Birot et al., 2020; Nekaris et al., 2020; Laidlaw et al., 2021).

Despite recent arboreal bridge studies from Peru (Gregory et al., 2017) and China (Chan et al., 2020), most arboreal wildlife bridge studies are from Australia, with multiple projects trialling a variety of designs throughout different regions (Abson, and Lawrence, 2003; Weston, 2003; Taylor and Goldingay, 2009). Collectively, over 10 arboreal bridge designs and variants have been trialled and tested including single ropes, rope tunnels (with and without square cross-sections), rope ladders, rope bridges with glider pole intervals, rope and mesh combination bridges, and woven rope bridges (Goosem et al., 2005; Taylor and

Goldingay, 2009; Soanes and van der Ree, 2010; Soanes et al., 2013; Soanes et al., 2015; Goldingay and Taylor, 2017). This has allowed for effective designs and techniques across different regions and various species in Australia to be increasingly well-defined and have influence on projects in other countries, such as South Africa (Linden et al., 2020), the United Kingdom (White and Hughes, 2019), and Japan (Minato et al., 2012). However, for lowland tropical rainforest systems in Meso and South America, information remains sparse. Only a few arboreal bridge projects have been executed and communicated (Teixeira et al., 2013; Balbuena et al., 2019; Laidlaw et al., 2021).

The Osa Peninsula in southwest Costa Rica consists of a network of protected areas containing both old growth and secondary rainforest, and a landscape matrix of cattle farms, oil palm, agriculture, and timber plantations. Thanks to the creation of the region's National Parks and Forest Reserves, the establishment of a pioneering Payment for Ecosystem Services scheme by the government, and a shift toward ecotourism. The region's ecosystems can still be considered functionally intact. Evidence from a recent region-wide terrestrial wildlife survey has shown significant signs of recovery in the distribution of several mammal species in the past three decades (Carrillo et al., 2000; Vargas Soto et al., 2021). The growing network of roads within the peninsula proves a significant ongoing threat to biodiversity by acting as ecological traps, physical barriers to wildlife movement, and simultaneously increasing hunting access (Coffin et al., 2007; Whitworth et al.,

2018). It is highly likely that the species most affected by these roads are those that utilise the forest canopy. Recent research from Amazonian Peru found that arboreal rainforest wildlife is more impacted by rainforest disturbance than terrestrial species (Tregidgo et al., 2010; Klimes et al., 2012; Whitworth et al., 2017), especially large-bodied arboreal mammals (Whitworth et al., 2019). The Osa Peninsula is home to a rich and diverse arboreal mammal community, comprising over 15 medium- to large-bodied species (Carrillo et al., 2000; Landmann et al., 2008; Beal et al., 2020) including several species of conservation concern, such as the endangered Central American spider monkey (*Ateles geoffroyi*; Cortes-Ortíz et al., 2021) and the endangered Central American squirrel monkey (*Saimiri oerstedii*; Solano-Rojas, 2021).

To better facilitate the potential movement for arboreal wildlife between forest areas within the Osa region, we installed and monitored the early use of 12 economically efficient arboreal wildlife bridges of three different designs. Here, we detail the location selection process (map analysis and ground truthing), the designs and materials utilized (including the durability and cost of each design), the construction and installation procedures, and the monitoring method. We also share the early-stage results of the first six months of monitoring from 12 bridges.

## Materials and methods

### STUDY AREA

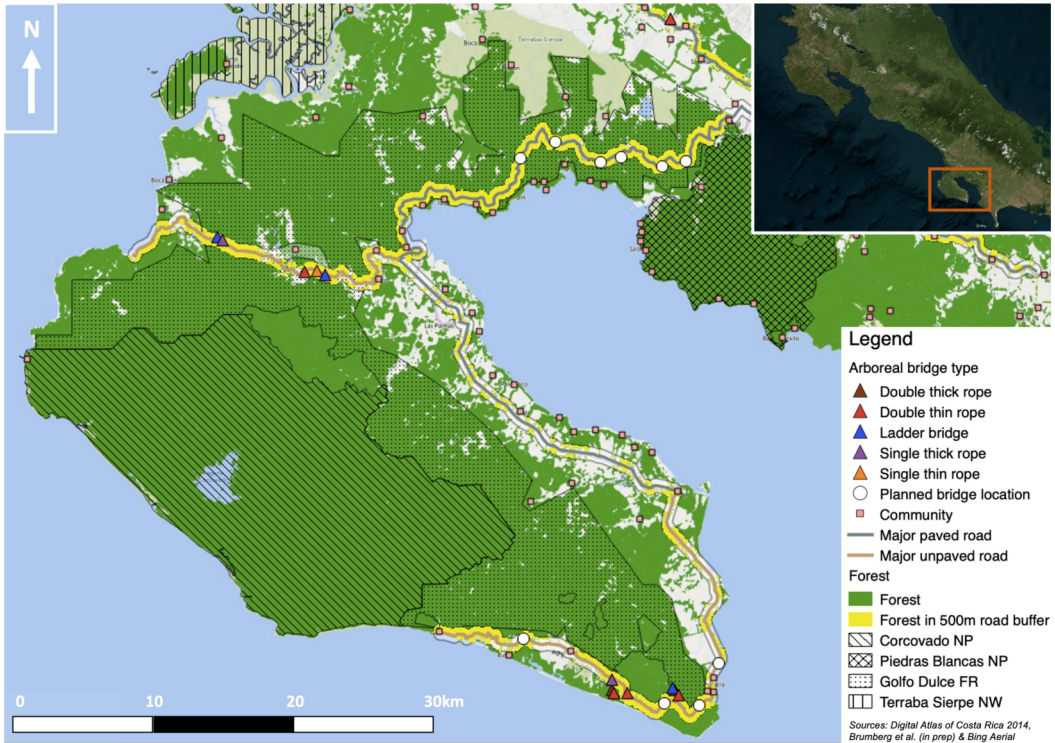
The Osa Peninsula in southwest Costa Rica is home to the largest remaining tract of Pacific lowland wet forest in Mesoamerica (Holdridge, 1967) and hosts four protected areas – Corcovado National Park (CNP), Piedras Blancas National Park (PBNP), Térraba del Sierpe National Wetland, and Golfo Dulce Forest Reserve (GDFR) (fig. 1), yet less than half of the original old growth area remains (Weissenhofer et al., 2001). Temperatures in the region range between 23.4°C and 28.8°C (Whitworth et al., 2018). Rainfall averages 3584 mm yr<sup>-1</sup> and is seasonal, with a rainy season from June to November and a dry season from December to May (Taylor et al., 2015).

The Osa region is traversed by two paved highways (fig. 2a) that connect the Osa with mainland Costa Rica, which restrict wildlife movements between the Osa and La Amistad International Park (the nearest large tract of forest), as well as unpaved roads (fig. 2b) that connect communities and farms within the Osa Peninsula. In addition to the two paved highways, this project focused on two unpaved roads because of their key location, forest cover, and quantity of traffic for access to CNP (see table 1 with reference to fig. 1 for details).

### BRIDGE SITE SELECTION

To identify priority locations for installing arboreal wildlife bridges in the region, we began with spatial analysis to highlight key areas along the focal roads where the infrastructure potentially disrupts connectivity between forest patches. We aimed to find areas with a minimum of 500-m forest cover buffer on both sides of the focal roads (fig. 1). A 500-m buffer was used, as it has been identified as the minimum substantial forest patch/buffer size to support mammal movements (Amiot et al., 2021), and therefore connecting these patches is key to increase wildlife distributions. This buffer was used to clip regional land use/land cover maps created in collaboration with NASA DEVELOP (unpubl. data) to extract the forest cover (mature forest and secondary forest) within 500 m on either side of the roads. Fifteen priority areas with high forest cover within the road buffer were identified for ground truthing.

The team visited all the priority areas identified by the map analysis and carried out ground assessments to confirm arboreal bridge suitability. The ground assessments included three key components: (1) confirm substantial forest on both sides of the road, as indicated by map analysis, (2) identify specific bridge location, and (3) confirm bridge length required. To confirm substantial forest, we checked the area (by foot and car) and spoke to local landowners. To identify the specific bridge location. We selected areas that had tall enough trees so a bridge could be installed above any electric and telecommunication lines present. Also, they were big enough to safely climb and



**Figure 1.** Map of the study area. Triangles indicate locations of 13 installed arboreal bridges colored by bridge design. White circles indicate the 10 locations identified for future bridge installation. Gray lines indicate major paved roads (Highway 245 and Interamerican Highway South Route 2), and brown lines indicate major unpaved roads. Pink squares indicate communities. Green indicates forest cover, and yellow indicates forest cover within a 500-meter-wide buffer on either side of major roads in the region. Black cross-hatches indicate Corcovado National Park, black perpendicular cross-hatches indicate Piedras Blancas National Park, black dotted area indicates Golfo Dulce Forest Reserve, and vertical lines indicate Terraba Sierpe National Wetland. Upper right inset: location of the Osa Peninsula in Costa Rica.

support bridge weight (pioneer species were not considered for these reasons), and with an appropriate structure (a large primary branch axis is ideal to stop bridges from slipping down). We also assessed the canopy vegetation at the selected trees to ensure a secure and straight bridge installation was possible (e.g., no obstructing lianas and branches). To determine bridge length, we measured road width (m), distance between the two host trees selected (m) and trunk circumference (m) using a tape measure. The GPS coordinates were recorded along with a descriptive note of physical characteristics (e.g., tree species, their distance from the road, and distance from closest electric pole) and a photo of the site. Based on the map analysis and subsequent ground truthing, we

identified 23 suitable sites to install bridges (installed bridges and planned bridge locations in fig. 1).

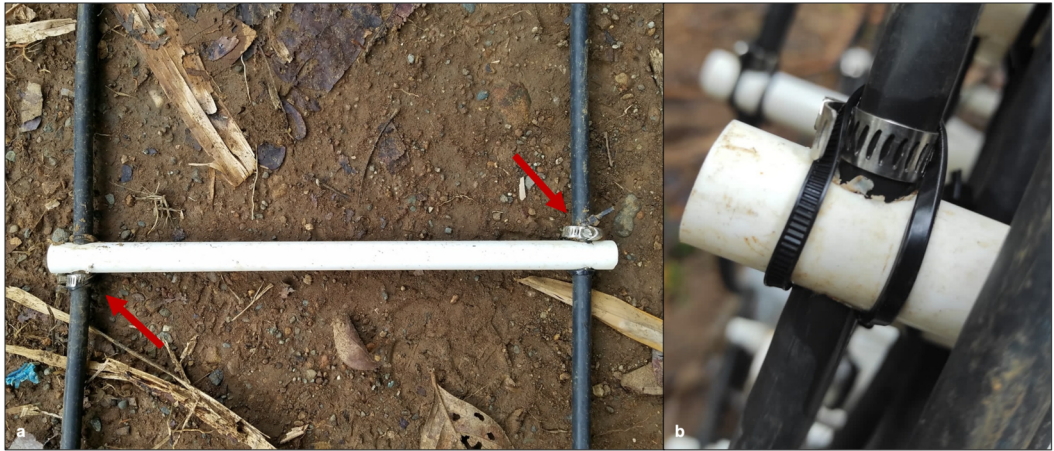
To easily compare data, multiple bridge sites were selected in close proximity to one another when possible, allowing different bridge designs to be tested in priority areas and minimize the differences between sites. This was not always possible due to the abundance and distribution of suitable sites to install bridges. While we did not assess key wildlife movement sites and include this in our site selection process, as we install more bridges across the region in priority areas in the future, we should be able to compare bridge use across designs at each site.



**Figure 2.** Osa’s road types, bridge designs installed and monitoring approaches: (a) Paved highway, (b) Gravel/dirt road including citizen science monitoring sign, (c) Single rope bridge, (d) Double rope bridge, (e) Ladder bridge, (f) Camera trap monitoring of bridges.

**Table 1.** Features and description of the main roads in the Osa region.

Road name	Road type	Road length (km)	Year established	Year paved	Description
Highway 245	Paved	76	1978	1989	Covers the inside edge of the Osa Peninsula running from Puerto Jiménez to Chacarita disconnecting PBNP from the GDFR
Interamerican Highway South Route 2	Paved	60	during 1970’s	during 1980’s	Connects the Osa Peninsula with San José and the rest of the Pan-American Highway, the southern portion, running from Palmar Sur to Rio Claro, stretching across the neck of the Peninsula
Rincón to Drake Bay	Unpaved	31	during early 2000’s	NA	Cutting across the whole Peninsula, through the GDFR above CNP
Highway 245 from Puerto Jiménez to Carate	Unpaved	44	During 1970’s	NA	Traverses the tip of the peninsula



**Figure 3.** Ladder bridge construction: a) PVC pipes were attached to the zipline with two stainless steel worm gear hose clamps on opposite sides, one above and one below the pipe, b) A plastic tie was attached around each metal clamp to ensure pipe security and bridge durability.

#### BRIDGE DESIGN, INSTALLATION, AND MONITORING

##### *Bridge design*

We selected three bridge designs based on their use and success in previous studies and the availability of materials in the region: (1) single rope bridge; herein single-rope; (Lindshield, 2016; Goldingay, and Taylor, 2017; Balbuena et al., 2019), (2) double rope bridge; herein double-rope (Chan et al., 2020), and (3) ladder bridge; herein ladder-bridge (Goosem et al., 2005; Lindshield, 2016). Each design required different materials, bridge construction, and installation methods.

The single-rope and double-rope designs consisted of 25 and 50 mm twisted synthetic polypropylene rope and 24" × 9.00 mm plastic zip ties (fig. 2c-d). The 50 mm rope came in 150 m rolls and was too heavy for the field team to transport, therefore it was cut to the needed length before going to the field. The 25 mm rope came in 100 m rolls and was light enough to transport, so the number of rolls was calculated, and the rope was cut to length in the field. The rope length required for bridge installation was the distance between the two selected trees plus an additional 10-15 m for connecting the bridge to the tree (the additional length varied based on the circumferences of the two selected tree trunks measured during ground assessments).

The ladder-bridge consisted of two pieces of 12.5 mm plastic coated zipline connected by 40 cm × 12 mm PVC rigid circular pipes (pipes herein), fixed by 1/2" and 3/4 – 1" stainless steel worm hose clamps (metal clamps herein), and 12" plastic zip ties, to form a ladder (fig. 2e). For construction of the ladder-bridge we used a drill with a 1/2" drill bit, screwdriver, and hacksaw. First, two pieces of zipline were cut to the required bridge length (calculated the same way as the single-rope and double-rope). The pipes were cut into 40 cm pieces using the hacksaw, and a hole was drilled at both ends at ~2.5 cm from the edge. The holes allowed the zipline to pass through easily but were not loose. Both ends of the ziplines were aligned before threading the pipes on. As a pipe was attached to the zipline, one metal clamp was introduced to each piece of zipline, on opposite sides of the pipe (fig. 3a). Pipes were spaced 35 cm apart along the bridge (a 20-m bridge would have ~55 pipes) and not installed on the final 5 m of both ends (required for connecting the bridge to the trees). After all pipes were attached, starting at the centre pipe, the metal clamps were tightened with a screwdriver. As an extra security measure, a zip tie was tightened around each metal clamp and the ends cut flush (fig. 3b). Finally, to test all pipes were connected

correctly and parallel, the bridge was hung from two trees at ground level.

### *Bridge installation*

Bridge installation required a minimum of four people: two climbers and two ground crew. We used a double-rope climbing system, which allows lowering the climber to the ground in case of emergency (designed and trained by Canopy Access LTD.). Once both trees were rigged, one climber would ascend with the equipment required for bridge installation (12 oz throw weights attached to a 1.8 mm × 50 m throw line flaked into a kit bag clipped on their harness, climbing slings of varying lengths, a small knife, lighter, a screwdriver, and – depending on the bridge type – either plastic zip ties or metal clamps). The branch of the tree used for bridge installation was selected from the ground, but as the climber ascended, they assessed all possible branches to confirm the best bridge installation location.

When the climber reached the selected branch, the throw line and weight were tossed as far as possible toward the road, clearing any branches understory vegetation and electrical lines (all bridges were able to be installed without the power being turned off due to the locations of the bridges in relation to electricity lines). The ground team detached the weight from the throw line and attached a 6-mm polyester intermediate rope. The climber pulled the throw line until reaching the intermediate rope. On the ground, the bridge was then attached to the intermediate rope, using a minimum of five clove hitch knots covered by electrical tape (at least on the first two knots) to allow for the bridge to be hoisted through the vegetation smoothly. The climber then pulled the rope, and the team on the ground obstacles. The climber then detached the bridge from the intermediate rope and began connecting it to the tree, while climber two ascended the second tree on the opposite side of the road. Once the bridge was connected on the first end, climber two pulled up the opposite end following the same method. When connecting the second end of the bridge to the tree, we ensured there was a slight slack between the two trees to account for any movement during storms. Once both ends of the

bridge were connected, the climbers tested the bridge was straight and connected tightly and made any final adjustments required to stabilize the bridge. In cases where the selected trees for bridge installation were disconnected from the rest of the forest patch, an additional bridge segment was installed to a third tree (a tree with natural connectivity to the forest patch/area).

The single-rope and double-rope were connected around the trunk using a branch as support to avoid any possible bridge slipping. If the trunk was too wide (e.g., *Ficus* sp.) or had multiple branches preventing a good bridge installation, the bridge was attached to a thick and healthy branch. Rope ends were wrapped around the trunk or branch a minimum of three times, and then secured with plastic zip ties. The number of plastic zip ties varied based on rope thickness (a minimum of 5 and a maximum of 12 zip ties). The zip ties were cut flush, and the ends of the rope burned with a lighter to avoid fraying. The ladder-bridge was connected to the main tree trunk utilizing a branch for support. Each zipline end (four in total) was wrapped a minimum of two times. The two ends were secured with two 3/4 or 1" metal clamps at the back of the trunk. An additional three metal clamps were used to keep the zipline together around the trunk. The distance between the last pipe of the bridge and the trunk was no larger than one meter.

### *Bridge monitoring*

To monitor wildlife using the arboreal bridges, a camera trap was installed on the same day facing the bridge from one side using either an adjustable strap or tree screw, following set-up protocol by Whitworth et al. (2016) and Bowler et al. (2017). The camera trap models used were Reconyx Ultrafire and Bushnell Core set to record 30 second videos with a 30 second interval between recordings. Camera traps were checked twice, first in March 2021 (three months after installation) and again in August 2021 (six months after installation). During camera trap checks, bridges are also checked with a special focus on the zip ties used for the rope bridges. If there is any sign of fatigue, they are replaced to avoid bridges falling and plastic littered. Wildlife in videos were identified

**Table 2.** A summary of the bridge material, additional materials to install the bridge, material cost, construction time and installation time for each of the three bridge designs (SRB – single rope bridge, DRB – double rope bridge and LB – ladder bridge) when installing a 20-m bridge (20-m bridge plus 10 m for installation). Construction time is based on a team of 2 people and installation time is based on a team of 4 people (2 of which are trained tree climbers) and does not include the time taken to rig the trees for climbing as this varies by the location (tree height and structure) not bridge design.

Design	Bridge material	Additional materials	Unit cost	Construction time	Installation time
SRB	25 mm synthetic polypropylene rope	12 plastic zip ties	~ US\$ 70	None	~3 h
	50 mm synthetic polypropylene rope	20 plastic zip ties	~ US\$ 295	~30 min	~4 h
DRB	25 mm synthetic polypropylene rope	24 plastic zip ties	~ US\$ 140	None	~4 h
	50 mm synthetic polypropylene rope	40 plastic zip ties	~ US\$ 590	~30 min	~5 h
LB	12.5 mm zipline 55 PVC pipes (1" × 40 cm)	110 plastic zip ties 110 1/2" metal clamps 12 1" metal clamps	~ US\$ 937	~6 h	~6 h

to species level and classified into three activity categories: (1) crossing – the animal travelled across the whole bridge, (2) perching – the animal used the bridge as a perch, and (3) investigating – the animals investigated the bridge but did not attempt a crossing or used the bridge as a perch. Due to the quantity of data collected so far, it is not yet possible to perform an adequate statistical analysis. Instead, we performed a descriptive analysis to obtain preliminary results. To execute preliminary analysis, we defined an independent wildlife event as one or more individuals perching on, investigating, or crossing an arboreal bridge separated by more than 30 minutes. In cases where we could confirm by visual observation that there was more than one individual for that species using the bridge within the 30 minutes, that was included as an independent wildlife event.

## Results

### GENERAL OVERVIEW

Thirteen arboreal wildlife bridges of three designs (Seven double-rope; three single-rope; and three ladder-bridges) were installed: 12 were installed between December 2020 and

February 2021, and a thirteenth bridge (double-rope) was installed in July 2021. Installation time, construction time, and cost information are included in the results from all 13 bridges, but only monitoring data collected from the first 12 of the 13 bridges was utilized in our preliminary results due to the short installation period. Bridge design costs ranged from US\$ 70 to US\$ 937, construction time ranged from 0 to 6 hours, and bridge installation time ranged from 3 to 6 hours (table 2). The 25 mm single-rope was the most inexpensive design and had the shortest installation time, while the ladder-bridge was the most expensive design and had the longest installation time (table 2).

Camera traps functioned on average  $157 \pm 37$  (mean  $\pm$  IC<sub>95%</sub>) trapping nights. Our preliminary results showed that independent wildlife events was detected for all three arboreal bridge designs. Overall, the camera traps detected 101 independent wildlife events (including perching, investigating and crossing) of eight species; 93 of which were mammals crossing (five species) and seven of which were birds perching (three species; table 3). Four of the 12 bridges experienced no wildlife activity; one of the three



**Table 3.** Number of independent wildlife crossings (determined as one or more individuals crossing an arboreal bridge separated by 30 minutes) by arboreal bridge design (7 double rope bridges, 3 single rope bridges; and 3 ladder bridges). In parenthesis is the number of arboreal bridges in which the independent events were recorded.

Species	Events (n)			Total
	Double rope bridge	Single rope bridge	Ladder bridge	
Kinkajou	33 (1)	0	5 (1)	33
Woolly opossum	3 (2)	21 (2)	0	29
Variiegated squirrel	18 (1)	0	0	18
Mouse opossum	10 (3)	1 (1)	0	11
White-faced Capuchin monkey	2 (1)	0	0	2
Total	66	22	5	93

ladder-bridge was used, two of the three single-rope were used, and five of the six double-rope were used (see supplementary table S1 for full independent wildlife events across bridge designs). The broad-winged hawk (*Buteo platypterus*) was the first species recorded in the study, perching on a single-rope one day after installation. The first mammal recorded crossing a double-rope was the kinkajou (*Potos flavus*), 26 days after installation. The first mammal recorded crossing a single-rope, and a ladder-bridge was the woolly opossum (*Caluromys derbianus*), 31 days and 170 days after installation, respectively.

#### BRIDGE DESIGN COMPARISON

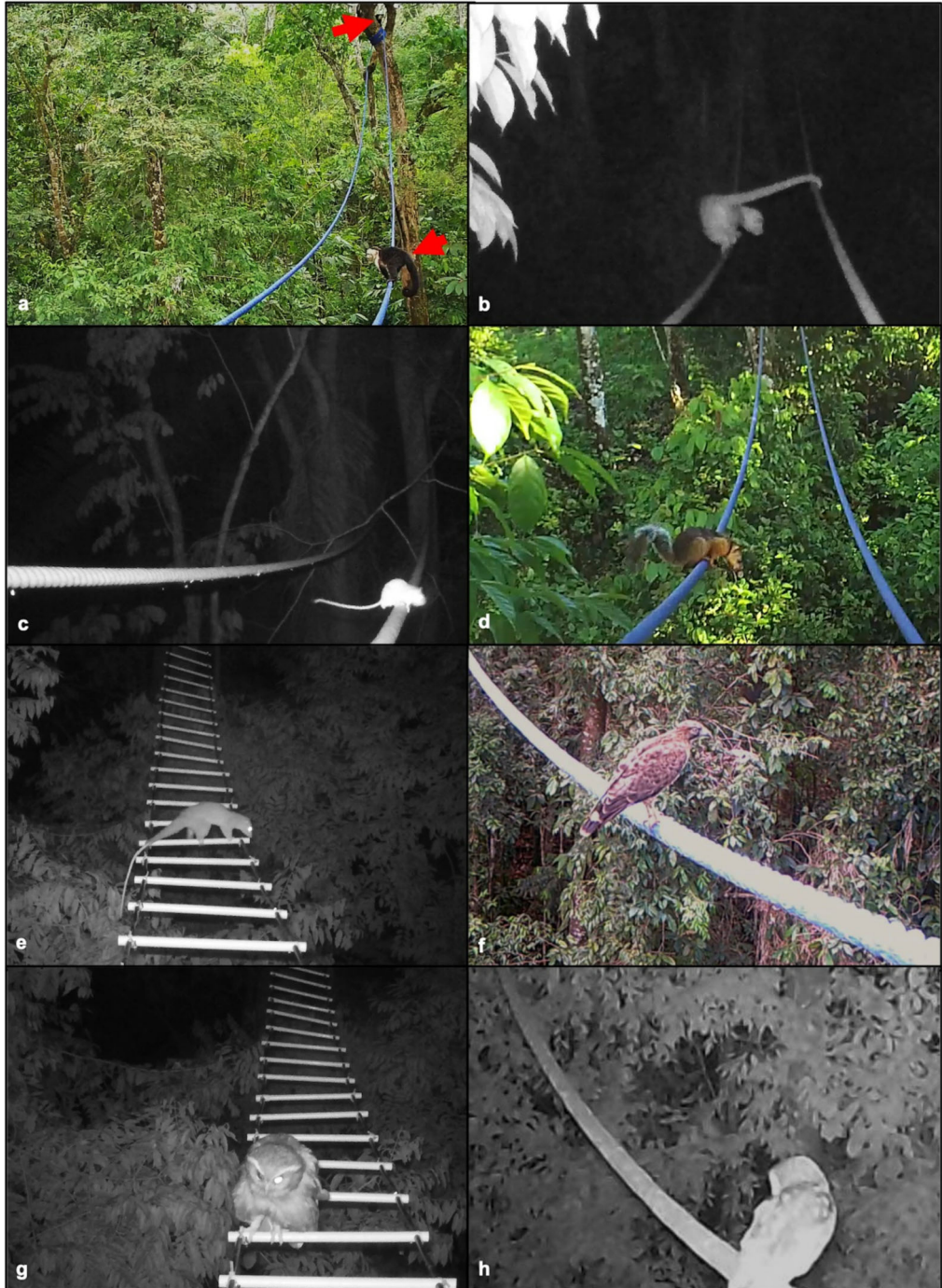
The number of species that used the arboreal wildlife bridges was different across the designs: the single-rope was used for crossing by the woolly opossum and mouse opossum (*Marmosa mexicana*) and for perching by the crested owl (*Lophotrix cristata*), the mottled owl (*Ciccaba virgata*), and the broad-winged hawk; the double-rope was used for crossing by the woolly opossum, the kinkajou, the variegated squirrel (*Sciurus variegatoides*), and the white-faced capuchin monkey (*Cebus capucinus*) and for perching by the crested owl; the ladder-bridge was used for crossing by the woolly opossum and for perching by the crested owl (fig. 4, table 3, and supplementary video S1). An Alfaro's pygmy squirrel (*Microsciurus alfari*) was seen investigating a single-rope but did not cross the bridge.

The mean number of wildlife crossings varied across arboreal designs. For the ladder-bridge, an average of 1.6 (SD = 2.88) independent events of species crossing were recorded, for the single-rope 7.33 (SD = 10.21), and 10.67 (SD = 20.87) for the double-rope. The number of wildlife crossings varied among species too. The higher values were seen for the kinkajou (mean = 33.0, SD = na) and the variegated squirrel (mean = 18, SD = na), followed by the woolly opossum (mean = 6.75, SD = 8.3), the mouse opossum (mean = 2.75, SD = 1.5), and the white-faced monkey (mean = 2, SD = na).

#### BRIDGE USE OVER TIME

Dividing wildlife crossings across the two camera trap checks (one after three months and one after six months of installation), the first check detected four mammal species crossing: the woolly opossum crossing a single-rope and a double-rope, the white-faced capuchin monkey crossing a double-rope, the kinkajou crossing a double-rope, and the variegated crossing a double-rope. The first check also detected 30 wildlife crossings, resulting in five out of the 12 arboreal bridges used, one single-rope and four double-rope.

The second check (six months after installation) detected three mammal species (one different from the first check; mouse opossum was detected but capuchin monkey was not), but two more bridges were used. During this period, 61 wildlife crossings were detected by a total of



**Figure 4.** Stills from the camera trap videos of the 8 species detected using the arboreal bridges: (a) white-faced capuchin monkey (*Cebus capucinus*); lower red arrow points out an individual crossing the upper arrow points out an individual that has already crossed waiting for the next individual to cross, (b) kinkajou (*Potos flavus*), (c) mouse opossum (*Marmosa mexicana*), (d) variegated squirrel (*Sciurus variegatoides*), (e) woolly opossum (*Caluromys derbianus*), (f) broad-winged hawk (*Buteo platypterus*), (g) crested owl (*Lophotrix cristata*), and (h) mottled owl (*Ciccaba virgata*).

three species using seven arboreal bridges, one ladder-bridge, two single-rope, and four double-rope; a kinkajou crossing double-rope, the variegated squirrel crossing double-rope, and the woolly opossum crossing single-rope, double-rope, and ladder-bridge.

## Discussion

Our early results and assessment of three simple arboreal wildlife bridge designs show rapid success in use by wildlife – at least 91 independent crossing events in the first six months post installation. We also show how preliminary wildlife use varies across bridge design in conjunction with the time and cost invested. However, it is too early to confirm the most suitable bridge design for arboreal wildlife species in the region, as more time, more bridges and a deeper understanding of wildlife pathways is needed. As the project continues, we will develop a better understanding of inter-site variation affecting crossing rates and locomotor preferences of wildlife due to continued camera trap monitoring and collection of covariates. Canopy structure (e.g., canopy height and cover) influences arboreal species movement and predation risk differently, which at the same time may impact the use of bridges (Goosem et al., 2005; McLean et al., 2016; Goldingay and Taylor, 2017; Chan et al., 2020). To further understand which factors – besides bridge design – influence their use, we recorded bridge length, bridge height, canopy cover around each bridge host tree, canopy cover above the road, and tree species. These covariates have not been included in the preliminary results due to a short monitoring period, but will be valuable covariates for longer term, more comprehensive analyses to understand factors that influence bridge use.

The ladder-bridge had the longest construction and installation time and was the most expensive design, but in the first six months received the lowest number of wildlife crossings. Wildlife activity for the ladder-bridge is lower than expected based on previous studies. For example, Weston et al. (2011), recorded eight arboreal mammal species utilizing ladder bridge designs; however, these results were

obtained from longer monitoring efforts during 2000-2010, with their first mammal crossing occurring seven months after bridge installation. We also used materials that, to our knowledge, have not yet been used for ladder bridges (rope is the common material for ladder bridges (Goosem et al., 2005; Weston et al., 2011), and it is possible that the materials we used require a longer habituation period.

The single-rope required no construction time, had the quickest installation time, was the least expensive bridge design (with a cost starting at US\$ 70), and had the second highest number of wildlife crossings. In comparison to other single-rope studies, the most common species utilizing this design were similar in body size across studies; 100 g-2 kg (Goldingay and Taylor, 2017; Balbuena et al., 2019), suggesting this design is well-suited for small-bodied mammals. However, we detected lower species diversity in wildlife crossings, with Goldingay and Taylor (2017) recording three mammal species over 14 months and Balbuena et al. (2019) recording 6 mammal species over 12 months (including two primates). We might expect an increase in the number of small-bodied arboreal mammal species using the single-rope over time, but this diversity of use likely relates to the given diversity of species within the eco-region. Another reason for single-rope to have use limited to small-bodied mammals, could be the potential of swaying linked with this design, which could increase with longer bridges and therefore is not a secure crossing option for large-bodied mammals (Goldingay and Taylor, 2017). Finally, our results from single-rope suggest that this design is more promising than Goseman et al. (2005), who reported no direct or photographic events of wildlife using single-RB.

The double-rope had the highest number of independent wildlife events, the second longest construction and installation time, and was the second most expensive bridge design (less than half the price of the ladder-B). Based on our early-stage results, the double-rope would be the most effective design to increase movement of arboreal mammals in the region. This design found the largest-bodied species using

the bridges – the kinkajou (*Potos flavus*) and the white-faced capuchin monkey (*Cebus capucinus*). Based on the camera trap footage, the double-rope could be preferred, particularly by these two larger species, due to the second rope for their tail to hold for support (fig. 4 and supplementary video S1). This is an important observation and consideration for neotropical primate species from the families Atelidae and Cebidae and the kinkajou – all of which have a prehensile or semi-prehensile tail essential for stability during locomotion in the canopy (Youlatos, 2003; Ruiz Palacios et al., 2017). This is not a characteristic observed in old world primate species (Lemelin, 1995). Therefore, for the neotropics, understanding how these closed canopy prehensile-tailed taxa use artificial structures above forest gaps is key for effective and scalable arboreal connectivity solutions.

We expect that over time, more species, especially large-bodied species, will increase their use of the bridges. Particularly for large-bodied arboreal mammals, studies have shown that sturdy bridge structures are more suited, and that they require a longer habituation period (Das et al., 2009). This is perhaps why we have not detected larger-bodied mammals utilizing the arboreal wildlife bridges yet in the Osa – such as the endangered Central American spider monkey. If this proves to be the case for the Osa region, longer term monitoring and durable designs will be required. Although more costly, the extended durability of ladder might pay off for these more sensitive species that require longer acclimatization. Yet, efficient (cheap and rapid) bridge designs such as the single-rope and double-rope could be used to identify high traffic wildlife pathways, followed by the installation of more robust permanent infrastructure in these prior identified hotspots (Soanes et al., 2013).

The efficient testing and design of arboreal wildlife bridges is key to understanding the needs of specific species (Soanes and van der Ree, 2015; Taylor, 2017). Large-bodied species such as the Hainan gibbon (*Nomascus hainanus*) for example have been observed using a double rope canopy bridge in Asia

(Chan et al., 2020). The rope was a different material than what we used (mountaineering-grade 13-mm diameter ropes), which substantially increases arboreal bridge cost. To attract spider monkeys to use the bridges in Osa, in addition to trialling different rope materials like the one used for the gibbon bridges, we could also trial a triple rope bridge design. This would be a build-on of the double-rope, adding a third rope, connected to the tree 30-60 cm above the double ropes. This would provide a third point of contact, allowing all hands, feet and tail to be in contact with the bridge, replicating natural movements and providing more security and support for this specialized brachiating prehensile tailed species. In addition to bridge design, we could trial and implement incentive or attractant techniques to kickstart bridge use. Baits and attractant lures have been used and proved to be effective at increasing wildlife detections in camera trap studies on the ground (du Preez et al., 2014; Ferreras et al., 2018). Moving forward, we will apply and test this in the canopy, utilizing vanilla essence and food baits to attempt to attract arboreal animals to the bridges and to potentially shorten the habituation period.

Another aspect to consider in determining the efficacy of arboreal bridge design is the protocol for monitoring; so far, camera traps have proven to be an effective monitoring tool (Wearn, and Glover-Kapfer, 2019). With only one camera trap on one end of the bridge, we could be missing wildlife activity and unable to confirm complete crossings. Studies show that utilizing multiple camera traps is often more effective than a single camera trap at detecting wildlife on the forest floor (Tobler et al., 2008; Pease et al., 2016). To ensure we are detecting all possible wildlife crossings we will now use paired camera trap monitoring (camera placed at both sides of the bridge), and additional cameras situated to look towards the forest as opposed to the bridge itself, so animals passing by or inspecting the infrastructure can also be observed.

In addition to camera trap monitoring, we encourage monitoring by citizen scientists, as



**Figure 5.** Design of signs that were installed under each bridge over a dirt road. We will adapt the sign design for the bridges installed above the paved highway, as traffic travels at higher speeds and will not be able to stop to read the sign in detail and examine the bridge.

evidence shows citizen science can be a cost-effective method to collect essential monitoring information over a large geographic area and can produce high levels of engagement (Aceves-Bueno et al., 2015). We installed informative signs below each bridge which link to an iNaturalist project (<https://www.inaturalist.org/projects/puentes-arbores-de-vida-silvestre-de-osa>) via a QR code (fig. 5). We have not yet received any observations on the iNaturalist project (signs were installed during November-December 2021). Also, we continuously upload the camera trap records to the project to share the results with the citizen scientist community.

In conclusion, each of our three bridge designs showed some level of use by Osa's arboreal wildlife in the short-term, and show potential for long-term use. The designs varied in cost and time in terms of bridge construction and installation, and increase in resource input did not correlate with an increase in wildlife use.

Continued monitoring will uncover the long-term efficacy and durability of our designs for this tropical case study. Trials of additional bridge designs and testing of incentive techniques are needed to build a bank of information to develop an effective wildlife arboreal bridge model which can be scaled-up and tested across tropical rainforest regions in Meso and South America. We will continue to tackle the conservation challenges bridges impose and work toward improved mitigation solutions for arboreal rainforest wildlife.

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### Statement of ethics

This research project used non-invasive methods and obtained and complied with research and conservation permits approved and distributed by SINAC (National System of Conservation Areas) in Costa Rica. Research permit No. SINAC-ACOSA-DT-PI-R-060-2020.

### Conflict of interest statement

The authors have no conflicts of interest to declare.

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### Author contributions

Concept and design; E.F, A.W, A.B, and M.H.C, raised funds and provided resources; E.F, M.H.C, and A.W, sourced permits; M.H.C, A.B, E.F, and C.P, field work and data collection; E.F, A.B, C.P, J.O, K.N, and N.R, map and data analysis; H.B, C.P, and E.F, manuscript writing and editing; E.F, A.B, C.P, K.N, N.R, H.B, and A.W.

### Data availability statement

All data generated or analyzed during this study are included in this article and its supplementary material files. Further enquiries can be directed to the corresponding author.

### Supplementary material

Supplementary material is available online at: <https://doi.org/10.6084/m9.figshare.19345460>

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