RESEARCH REPORT

doi: 10.1111/emr.12568

Mitigating the effect of linear infrastructure on arboreal mammals in dense forest: A canopy bridge trial

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Summary **Roads and other linear infrastructure create treeless gaps that can limit the movement of non-flying, arboreal animals. These negative effects are particularly strong in dense forests, where even narrow infrastructure corridors represent a significant change in habitat structure. Artificial canopy bridges are an increasingly common approach to mitigating the barrier effect of roads and other linear infrastructure on the movement of arboreal mammals; however, questions remain about the success of various designs for different species. Here we conduct an experimental evaluation of the response of a critically endangered possum, Leadbeater's Possum (*Gymnobelideus leadbeateri*), to two artificial canopy bridge designs: single-rope bridges and ladder bridges. We found that both bridges were used by Leadbeater's Possum and five other species of arboreal marsupial to cross narrow, forestry roads. However, Leadbeater's Possums crossed ladder bridges 13 times more often than the single-rope design (average of 564.5 and 41.75 crossings per design respectively). Radiotelemetry conducted on four Leadbeater's Possums prior to bridge installation detected no road crossings, providing preliminary evidence that the bridges improved cross-road movement. Ladder bridges appear to be the better design choice for a wider range of arboreal marsupials as they were used more frequently, offer greater stability, and provide better predator avoidance than single-rope designs.**

Key words: *connectivity, fragmentation, gap crossing, Leadbeater's Possum, road ecology, wildlife crossing structures.*

Implications for Managers

- Canopy bridges should be provided for Leadbeater's Possum where linear infrastructure cannot be avoided within their preferred habitat.
- Ladder-style bridges were preferred by Leadbeater's Possum over single-rope designs, and should be selected when Leadbeater's Possum are the target species.
- Ladder-style bridges appear to offer greater stability for larger species and enable predator avoidance for smaller species, and therefore we recommend their use in favour of single-rope designs to cater for arboreal marsupials.

Introduction

Roads and other linear infrastructures create gaps in habitat that can limit the movement of wildlife, with negative consequences for population persistence (Forman & Alexander 1998; Coffin 2007). Non-flying arboreal animals are particularly vulnerable to this 'barrier effect', whereby movement through woodland or forest is reduced or completely restricted by linear infrastructure (Laurance *et al.* 2009; Taylor & Goldingay 2010; Soanes & van der Ree 2015). The severity of the effect depends on the width of the road, habitat type, and movement ecology of the species. For example, some species frequently traverse smaller clearings or roads with low traffic volume but rarely cross larger roads (van der Ree *et al.* 2010; Minato *et al.* 2012; Bista *et al.* 2022). However, even narrow infrastructure corridors may cause significant habitat fragmentation for gap-sensitive species, and these impacts can be more severe within dense forests, causing a sudden change in microclimate, exposure to elements, and a disruption in an otherwise connected forest canopy (Wilson *et al.* 2007; Laurance *et al.* 2009; Ascensão *et al.* 2019). The impacts of existing linear infrastructure and the predicted expansion of the various networks in the coming decades pose significant threats to arboreal animals around the world and more must be done to prevent population declines.

Canopy bridges are a potentially powerful tool to mitigate the barrier effect of roads and other linear infrastructure on the movement of arboreal mammals (Soanes & van der Ree 2015). A wide range of designs have been implemented worldwide, including retained canopy connectivity (Gregory *et al.* 2014; Balbuena *et al.* 2019), rope ladders

(Goldingay *et al*. 2013; Soanes *et al*. 2013; Yokochi & Bencini 2015), wooden or bamboo bridges (Das *et al*. 2009; Teixeira *et al*. 2013; Linden *et al*. 2020) and metal gantries (Minato *et al*. 2012). While these studies provide extensive evidence that a wide range of arboreal mammals will use artificial canopy bridges to cross roads, with resulting benefits for gene flow and population persistence (Taylor & Goldingay 2009; Soanes *et al*. 2018), questions about the most appropriate design remain. For example, single-rope bridges are a cheaper option than more complex designs; however, knowledge of their success is limited (Goldingay & Taylor 2017). The effectiveness of different designs is likely to be strongly linked to the locomotor specialisation of the target species and the size and type of the gap to be crossed. For example, Weston *et al*. (2011) found no definitive evidence of a single-rope bridge being used by rainforest possums, while Maria *et al*. (2022) found single-rope bridges were used by eight species of arboreal mammal in the tropical forests of Bangladesh. Other studies show primates preferred a single-pole bridge to a ladder design (Linden *et al*. 2020; Garcia *et al*. 2022). In some cases, closely related species may exhibit different preferences despite having similar size and locomotor patterns (Goldingay & Taylor 2017). Field trials that experimentally test the function of different designs are critical to provide a strong evidence-base from which best-practice recommendations can be made (Goldingay & Taylor 2017; Narváez-Rivera & Lindshield 2022; Yap *et al*. 2022).

Leadbeater's Possum (*Gymnobelideus leadbeateri*) is a small (100–160 g), nocturnal arboreal marsupial in south-east Australia under increasing threat from linear gaps in their preferred forest habitat. The species was listed as 'critically endangered' (IUCN) following population declines due to habitat destruction and catastrophic fires, and the remaining populations occur in disjunct pockets of wet sclerophyll forest (Blair *et al*. 2018; Lindenmayer *et al*. 2021). The forests have an extensive history of timber harvesting and tourism, and consequently have a vast network of roads, varying from unsealed, single-lane tracks to sealed, high-volume roads. As a consequence of recent major wildfires, many fire-breaks and access tracks have also been constructed throughout large areas of forest as part of the fire prevention and emergency response. While an essential component of fire management, these linear features also have the potential to significantly impact Leadbeater's Possum populations, creating gaps of up to 40 m wide (though larger gaps can be created during emergencies to control wildfires). Little is known about the capacity of Leadbeater's Possum to cross large gaps. However, gap-crossing is anticipated to be low given that the species is a forest obligate and uses dense, mid-storey shrubs and trees to move throughout their habitat (Blair *et al*. 2017). Their willingness to use artificial canopy bridges has not been evaluated. Given the extent of existing roads and the proliferation of fire-access tracks throughout their habitat, research into the response of Leadbeater's Possum to habitat gaps and potential mitigation options is required to guide future emergency responses and conservation efforts.

Here, we conduct an experimental evaluation of the response of Leadbeater's possum to two artificial canopy bridge designs. Following a small-scale field study of possum locations and gap-crossing, we installed eight canopy bridges across two sites, comparing the use of two designs by Leadbeater's Possum and other arboreal mammals.

Methods

Overview

Our study was conducted within the montane ash forest of the Victorian Central Highlands, Wurundjeri Woi Wurrung Country, southeast Australia. We selected two sites, each along a narrow forestry road, selected to be as similar as possible in vegetation type, road characteristics, and presence of Leadbeater's Possum in the surrounding habitat. Sites were independent, approximately 4-km apart and well beyond the maximum reported daily movement distance (600 m) and dispersal distance (1460 m) of Leadbeater's Possum (Blair *et al*. 2017). Field surveys and radio-tracking provided baseline information on the location of Leadbeater's Possum at each site and the degree to which they crossed the road. Four artificial canopy bridges (two of each design) were then installed at each site (eight bridges total) in a trial of two designs: single-rope and rope ladder. Cameras were used to monitor bridges after their installation.

Study area

The two roads studied were Dowey Spur Road and Roman Creek Road near Powelltown, Victoria (37°50′S, 145°50′E). These unsealed roads predominantly cater to forestry and management vehicles, with a low traffic volume of 1–2 vehicles per day (with some additional tourist traffic on weekends). The total road width includes the road surface of compacted gravel and road shoulders of short grass, creating a gap of approximately 15 m between trunks on either side of the road, and a canopy gap of 5–10 m. The surrounding forest was wet sclerophyll dominated by *Eucalyptus regnans* and *E. obliqua* (30–40 m high) with a dense mid-storey of *Acacia* spp. (5–10 m high). The forest at both sites was mixed-age, including regrowth and standing dead trees from a wildfire and post-fire salvage logging in 1983. Sites were chosen for their similar habitat on both sides of the road (not recently burnt, presence of large trees with hollows, and *Acacia* spp.) and previous records of Leadbeater's Possum.

Seven other species of arboreal mammal occur in the area including Yellow-bellied Glider (*Petaurus australis*), Krefft's Glider (*Petaurus notatus*, formerly *breviceps*, Cremona *et al*. 2021), Feathertail Glider (*Acrobates pygmaeus*), Greater Glider (*Petauroides volans*), Mountain Brushtail Possum (*Trichosurus cunninghami*), Eastern Pygmy Possum (*Cercartetus nanus*) and Eastern Ringtail Possum (*Pseudocheirus peregrinus*), along with a scansorial species, the Agile Antechinus (*Antechinus agilis*).

Before: Radio-tracking to establish baseline movement

Initial trapping surveys were conducted at four sites to identify potential locations for the artificial canopy bridges trial. In brief, 64 traps were set at each site for seven consecutive nights between 30 August and 6 September 2011 (224 trap nights per site, Harrison *et al*. 2018). Traps were placed on both sides of the road at each site. We used a combination of Elliott traps (Type A, 33 × 10 × 9 cm) and PVC pipe traps (Winning & King 2008) at each site, baited with mixture of peanut butter, rolled oats and honey, and placed on large, hollow-bearing trees (and the trees or shrubs immediately adjacent) to maximise the probability of capture. These trapping methods specifically targeted Leadbeater's Possum.

The capture rate for Leadbeater's Possums was low (Harrison *et al*. 2018). We captured nine Leadbeater's Possums (5 females, 4 males) at three of the four sites. Of these, only four animals were suitable for collaring: two at Dowey Spur Road (1 female, 1 male) and two at Roman Creek Road (1 female, 1 male). At each site, animals were only captured on a single side of the road. The fitted collars were single-stage whip antenna radio-collars (150 MHz; Sirtrack, New Zealand) weighing less than 5% of the animals' body weight. Collars were only fitted to resident adults (identified by recaptures).

Tracking was conducted using a hand-held three-element Yagi antenna (Sirtrack) and VHF receiver (Australis 26k, Titley Electronics and Telonics TR-4). We collected two types of location data: directional fixes to identify road crossing behaviour, and den fixes to identify den (nesting) trees. As the species is nocturnal, directional fixes were obtained between dusk and dawn (20:20–05:30; Australian Eastern Standard Time) by standing on the roadside and determining the side of the road on which the animal was located. Each animal was located 1–9 times per night, allowing at least 1 h between subsequent fixes. Directional fixes were collected during two, 1-week sessions between 17 October and 18 November 2011, for 14 nights total. Diurnal fixes were conducted during daylight hours when the animals would be sheltering within their dens between 3 October and 18 November.

Additional trapping surveys were conducted at each site to check the condition of collared animals (4–7 October 2011) and remove the collars (20 December 2011).

Installation of canopy bridges

Artificial canopy bridges were installed between June and July 2012 (hereafter referred to as bridges). We trialled two bridge designs: a single strand of rope (40 mm diameter) and a 'ladder' design (Fig. 1). The ladder design consisted of three or four parallel strands of rope (each 35 mm diameter) intersected by PVC pipe cross-bars at 1-m intervals. All bridges were approximately 15 m long and constructed of UV-stabilised, marine-grade rope. No additional tubes or shelter sites were installed.

Two bridges of each design were installed at each site (four bridges per site). The distance between bridges within a site ranged from 15 to 90 m, creating approximately 130 m of mitigated road at each site. All bridges were positioned within 50–100 m of den trees identified during radio-tracking and arranged to ensure animals had equal access to both designs. The bridges were attached directly to large *Eucalyptus* spp. trees on the edge of the road at approximately 5–6 m high. Where feasible, additional feeder ropes were used to better link the bridges to the surrounding vegetation (up to 3 per end).

After: Monitoring canopy bridges using cameras

We installed Buckeye X7D cameras (Buckeye, USA) on 7 April 2014 21 months after bridges were installed, allowing time for wildlife to habituate to the structures. One camera was placed at each end of each bridge allowing the detection of complete crossing sequences in which animals are recorded entering the bridge through one camera and leaving via the other. Once the passive-infrared sensor was triggered by animal movement, the cameras recorded a 20-s video, with a 30-s delay between triggers. As we were predominantly interested in the movement of nocturnal species, cameras were programmed to operate between 18:00 and 06:00 h (Australian Eastern Standard Time), coinciding with approximately dusk and dawn each day.

All cameras were connected to a ground base-station at each site, which allowed us to access the data and check the status of cameras without needing to directly access the cameras in the canopy. We inspected the base-station every 3–4 weeks to replace the batteries (lead-acid, 12 V), ensure camera clocks were calibrated and download images. The cameras were operational almost continuously throughout the 12-month monitoring period (7April 2014–8 April 2015), with the total operation time ranging from 335 to 351 nights for each bridge.

Processing and analysis of camera data

All videos were manually inspected for the presence of wildlife. We recorded the date, time, species, direction of travel, and any other notes of interest. Where an animal triggered multiple consecutive videos with less than 1 min between videos (i.e. an animal was in front of the camera for an extended period of time) these were recorded as a single 'event'. Videos from opposite cameras on each bridge were cross-referenced to identify complete crossing sequences where possible. We focused on the activity of arboreal mammals using the bridges; however, the presence and activity of other species, such as birds, and activity on the ground that triggered the cameras (such as vehicles or humans) were also noted.

Activity by arboreal mammals was categorised into four crossing types – complete confirmed, complete unconfirmed, partial, or unidentifiable – based on the animal's behaviour and direction of travel (Table 1). For a crossing to be considered confirmed, a corresponding video from the opposite side of the bridge must have been recorded, resulting in a sequence showing the animal entering the bridge and moving away from the camera on

Figure 1. The study site and bridge designs: (a) the narrow road with ladder bridge (foreground) and single-rope bridge (background) visible, (b) view of a single-rope bridge from below, (c) view of a ladder rope bridge from below.

Table 1. Definition of crossing types for arboreal mammals

Crossing category	Definition
Complete confirmed	Animal observed entering bridge through one camera, moving across the bridge towards the opposite side until out of sight. Animal then observed moving towards the camera at the opposite side of the bridge, exiting the bridge on the opposite side of the road (matching the date and approximate time)
Complete unconfirmed	Animal observed entering bridge through one camera, moving with intent across the bridge towards the opposite side until out of sight, however, is not recorded on the opposite camera – most likely due to quick movement. Not observed returning to the same side
Partial	Animal observed moving out onto bridge before turning around and exiting the bridge on the same side
Unidentifiable	Animal present in video, however, moves so quickly that species and behaviour cannot be reliably determined

one side of the bridge, then moving towards the camera and exiting the bridge on the other side. Unconfirmed crossings were those that were likely to represent complete crossings based on the animal's behaviour and direction of travel; however, they could not be verified by a second camera. This can occur when the animal's movement failed to trigger one of the cameras, for example, if it was fast-moving or jumped from the bridge into the roadside vegetation before reaching the opposite camera.

We used a Poisson regression to investigate the effect of bridge design (ladder or single-rope) on the number of complete crossings (combining confirmed and unconfirmed) by arboreal mammals (R version 4.1.1, R Core Team, 2021). Analyses were conducted separately for each species. Species that were recorded at less than four bridges were excluded.

Results

Radio-tracking

A total of 315 nocturnal directional fixes and 69 diurnal den fixes were obtained for the four Leadbeater's Possums prior to bridge installation (46–94 fixes per individual). We found no evidence that Leadbeater's Possums crossed either road – animals were never located on the opposite side to their previous location. Four den trees were identified, one at Dowey Spur Road, three at Roman Creek Road, all within 50 m of the road edge.

Frequency of crossings by arboreal mammals

We detected six species of arboreal marsupial on the canopy bridges from 4,763 observations (complete and partial crossings), including the Leadbeater's Possum (n = 2,693 observations), Agile Antechinus (n = 869), Eastern Ringtail Possum (n = 512), Mountain Brushtail Possum (n = 592), Krefft's Glider (n = 21) and Feathertail Glider (n = 3). All species were observed making complete crossings of at least one bridge. All eight bridges were used by at least one species to cross the road (Table 2, Fig. 2). An additional 76 observations were unidentifiable.

Leadbeater's Possums were the most common species to cross the bridges, with an overall crossing rate of 6.9 crossings per night. While they were observed using each of the eight bridges, crossing rates varied ranging from 0.1 to 2.35 per night at each bridge. Agile Antechinuses were detected crossing seven of the eight bridges, Eastern Ringtail Possums six, Mountain Brushtail Possums four, Feathertail Gliders two, and Krefft's Gliders at only a single bridge. The generally low incidence of partial crossings suggests that animals were confident using the bridges to cross the road. However, some bridges had a higher proportion of partial crossings than complete crossings, potentially indicating hesitancy at that location

Table 2. Crossing activity by arboreal marsupials at each canopy bridge

	Roman Creek Road				Dowey Spur Road			
Bridge no.	RCR1	RCR2	RCR3	RCR4	DSR5	DSR6	DSR7	DSR8
Bridge design	Ladder	Single	Ladder	Single	Ladder	Single	Single	Ladder
No. Monitoring nights	350	351	351	351	351	351	351	335
Leadbeater's Possum (*n* = 2693)								
Total activity	97	21	857	74	868	15	127	634
Partial crossings (%)	13%	57%	8%	14%	10%	67%	30%	11%
Total crossings (% confirmed)	84 (4%)	9 (89%)	825 (69%)	64 (80%)	786 (37%)	5 (20%)	89 (84%)	567 (78%)
Crossings per night	0.24	0.03	2.35	0.18	2.24	0.01	0.25	1.69
Agile Antechinus (*n* = 869)								
Total activity	96	48	144	303	257	20	1	0
Partial crossings (%)	13%	17%	9%	8%	4%	30%	0	–
Total crossings (% confirmed)	84 (0%)	40 (0%)	131 (51%)	279 (88%)	247 (11%)	14 (0%)	1 (0%)	–
Crossings per night	0.24	0.11	0.37	0.79	0.70	0.04	0.003	–
Eastern Ringtail Possum (*n* = 512)								
Total activity	59	17	76	192	97	0	0	71
Partial crossings (%)	12%	6%	5%	5%	9%	–	–	3%
Total crossings (% confirmed)	52 (2%)	16 (87%)	72 (79%)	183 (96%)	88 (87%)	–	–	69 (84%)
Crossings per night	0.15	0.05	0.21	0.52	0.25	–	–	0.21
Mountain Brushtail Possum (*n* = 592)								
Total activity	0	0	3	4	518	0	0	66
Partial crossings (%)	–	–	67%	25%	9%	–	–	21%
Total crossings (% confirmed)	–	–	1 (0%)	3 (33%)	472 (78%)	–	–	52 (77%)
Crossings per night	–	–	0.003	0.01	1.34	–	–	0.16
Krefft's Glider (*n* = 21)								
Total activity	7	3	2	5	1	0	2	1
Partial crossings (%)	29%	100%	100%	100%	100%	–	100%	100%
Total crossings (% confirmed)	5 (0%)	–	–	–	–	–	–	–
Crossings per night	0.014	–	–	–	–	–	–	–
Feathertail glider (*n* = 3)								
Total activity	0	1	1	1	0	0	0	0
Partial crossings (%)	–	100%	0	0	–	–	–	–
Total crossings (% confirmed)	–	0	1 (0%)	1 (100%)	–	–	–	–
Crossings per night	–	0	0.003	0.003	–	–	–	–

Total activity is the overall number of detections observed at a bridge for a given species. See Table 1 for definitions of crossing types.

Figure 2. Arboreal marsupials crossing the rope bridges: (a) Leadbeater's Possum, (b) Eastern Ringtail Possum, (c) Feathertail Glider, (d) Eastern Ringtail Possum.

(e.g. Leadbeater's Possums at single-rope bridge 2 and 6, Mountain Brushtail Possums at ladder bridge 3; Table 2). Krefft's Gliders had twice as many partial crossings as confirmed crossings.

Effect of bridge design on crossing rate

Ladder bridges were used more frequently than single-rope bridges by Leadbeater's Possum and Mountain Brushtail Possum; however, there was little difference in the number of crossings by Agile Antechinus and Eastern Ringtail Possum at the two bridge designs (Fig. 3). The average number of crossings by Leadbeater's Possum was approximately 13 times higher at ladder bridges (mean = 565.5, SE = 170.2) than single bridges (mean = 41.7, SE = 20.7). Statistical analysis revealed single-rope bridges had a strong, negative effect on the number of crossings by Leadbeater's Possum and Mountain Brushtail Possum, and a weak, negative effect on the number of crossings by Agile Antechinus and Eastern Ringtail Possum (Table 3).

Behavioural observations and other wildlife

The two bridge designs elicited different behavioural responses by different species (see Supporting Information for Videos S1–S5). Video footage showed Leadbeater's and Eastern Ringtail Possums were adept at using both the single-rope and ladder designs. When using the ladder design, animals tended to move along the outer edge of the bridge rather than using the central part. Leadbeater's Possums also frequently ducked through the ladder rungs and under the bridge during their crossing. Agile Antechinus moved along the ropes in a 'spiral' fashion – alternating between moving on top of and along the underside of the rope – consistent with their natural movement pattern along tree branches. The Mountain Brushtail Possums were tentative on the single rope and occasionally slipped to hang upside down, unable to right themselves.

Most crossings were completed quickly (<2 min) and all crossings by Leadbeater's Possum, Agile Antechinus, Eastern Ringtail Possum and Feathertail Glider were completed in less than 16 min. Mountain Brushtail Possums were more likely to spend longer on the bridges, moving slowly or pausing to sit on the structures, with one crossing taking 55 min.

Nocturnal raptors were recorded perching on all bridges. Two species could be identified; Tawny Frogmouth (*Podargus strigoides*) and Southern Boobook (*Ninox boobook*). A Southern Boobook was observed feeding on an Agile Antechinus while perched on the single-rope bridge. A Leadbeater's Possum escaped attack from an unidentified owl by darting through the ladder structure and hiding below the bridge as the bird swooped.

We observed no signs of inter-species aggression, even when two species attempted to cross the bridge in opposite directions at the same time, which was observed six times. However, we observed two Leadbeater's Possums fighting on one of the ladder bridges, with one animal eventually tossing the other from the side of the structure.

Other species detected on the bridges included birds (n = 1339 records), insects (n = 11), skinks and geckos (n = 6), though these do not represent crossings. The movement of other wildlife or people on the ground or flying past (e.g. birds and bats) also occasionally triggered the cameras. People were twice recorded attempting to interfere with the bridge or camera equipment.

Discussion

The artificial canopy bridges in this study facilitated cross-road movement by a range of arboreal marsupials, including the first records of canopy bridge use by Leadbeater's Possum. Crossing rates were high

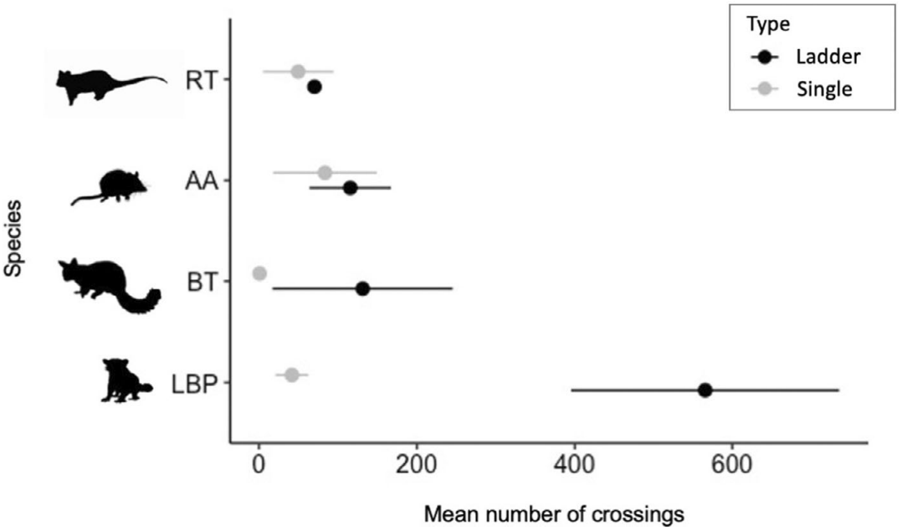

Figure 3. Mean number of crossings and standard error for arboreal marsupials at each bridge designed by Eastern Ringtail Possums (RT), Agile Antechinus (AA) Mountain Brushtail Possum (BT) and Leadbeater's Possum (LBP). Animal silhouettes designed by Michael Scroggie (RT), Robbi Bishop-Taylor (AA), Gavin Prideaux (BT) and Steven Traven (LBP).

Table 3. Parameter estimates from Poisson regression conducted for four species of arboreal marsupial, showing the effect of single-rope bridge on the number of crossings relative to the ladder bridge design

Species	Parameter	Mean	Standard error
Leadbeater's Possum	Intercept	6.34	0.021
	Single bridge	−2.61	0.080
Agile Antechinus	Intercept	4.75	0.047
	Single bridge	−0.32	0.072
Eastern Ringtail Possum	Intercept	4.25	0.059
	Single bridge	−0.35	0.093
Mountain Brushtail Possum	Intercept	4.88	0.044
	Single bridge	−5.16	0.579

All models were statistically significant to $P < 0.0001$.

overall, with some structures crossed 20 times in a single night. Six of the eight arboreal species known to be present in the area were detected on the bridges. This adds further evidence that artificial canopy bridges can cater to a wide range of arboreal mammals (Weston *et al.* 2011; Birot *et al.* 2020; Chan *et al.* 2020). However, only one of the three gliding species (Krefft's Glider) used the bridges, albeit rarely. This likely reflects the fact that the gap being mitigated was well within gliding distance for Yellow-bellied and Greater Gliders. Overall, the bridges were successful at promoting the movement of Leadbeater's Possum over narrow road gaps.

Ladder-style bridges may be more suitable for arboreal marsupials than single-rope designs. Leadbeater's Possum showed a clear preference for ladder bridges, using them 13 times more frequently than single-rope bridges. Mountain Brushtail Possums also appeared to prefer the ladder bridges and physically struggled to cross the single-rope bridges. In contrast, the Eastern Ringtail Possum and Agile Antechinus were adept at crossing the single-rope bridges and there was little evidence of a preference for either design. These findings generally align with our expectations based on species size and movement capability. For example, ringtail possums are agile and frequently traverse narrow branches and powerlines (Van Helden *et al.* 2020) while the larger brushtail possums may require the additional stability offered by ladder bridges. In some videos, Mountain Brushtail Possums slipped underneath the single-rope bridge and could not right themselves, completing the crossing upside-down. Studies have shown ladder bridges are used by other arboreal marsupials including Western Ringtail Possums (*Pseudocheirus occidentalis*, Yokochi & Bencini 2015), small gliding species (Goldingay *et al.* 2013; Soanes *et al.* 2015) and a range of tropical forest mammals (Weston *et al.* 2011). The additional stability provided by the ladder bridges may therefore accommodate a larger range of species than a single rope alone. Road agencies, land managers, and environmental authorities looking to minimise the impact of linear infrastructure on arboreal marsupials should opt for ladder bridges rather than single ropes to cater to the widest range of species. Canopy bridges should be used to minimise the impact of new roads and other linear clearings as well as be retrofitted to improve movement across existing roads.

It is unclear what is driving Leadbeaters' Possum's preference for ladder bridges over single given that they are relatively small and highly agile. However, it may be that the more complex structure offers greater perceived protection from predation relative to the single-rope design. Predation of animals as they use wildlife crossing structures is a commonly raised concern, though there is little evidence of it occurring to date (Little *et al.* 2002; Ford & Clevenger 2010; Mata *et al.* 2015) and no evidence showing that predation at a wildlife crossing structure occurs at a higher rate than the surrounding environment. In contrast to previous work quantifying predation risk at canopy bridges (Soanes *et al.* 2017) nocturnal raptors were common within our study landscape and were observed at all of the bridges. We recorded one predation attempt at the ladder bridges, where a Leadbeater's Possum avoided an owl by darting through the complex ladder structure and hiding below the bridge. Leadbeater's Possum frequently ducked below the ladder bridge during their crossings, potentially as a predator avoidance behaviour. While predation at a wildlife crossing structure is not evidence of a 'prey-trap', it could be a concern where the local population is low (i.e. proportionate mortality), or the risk of predation causes animals to avoid crossing. The added protection provided by the ladder bridge further supports the use of this design as a crossing structure for small, arboreal marsupials.

Comparing the movement of Leadbeater's Possums across the bridges with the radio-tracking data collected before the bridges were installed suggests that these bridges allow movement that would not have otherwise occurred, or would rarely occur. The radio-tracking data collected before bridges were installed were limited (four individuals tracked for 2 weeks); however, they provide evidence that road-crossing was limited at these sites prior to mitigation. Leadbeater's Possums were detected using canopy bridges more than 2000 times during the 12-month monitoring period, with crossings occurring on 297 of a possible 351 monitoring nights and multiple crossings per night. Had Leadbeater's Possums been crossing the road at this frequency before the bridges were built, it is likely that at least one crossing would have been detected during the radio-tracking. Therefore, we tentatively conclude that the narrow forest roads without canopy- or midstorey connectivity restricted the movement of Leadbeater's Possums at our sites, and that this can be mitigated through the use of artificial canopy bridges. Further, providing safe, arboreal pathways reduces the risk of predation by feral predators, which were observed at the site (McComb *et al.* 2019). Based on these findings, we recommend that infrastructure or management initiatives that create gaps within forests occupied by Leadbeater's Possum (such as Forest Fire Management's 'Strategic Fuel Breaks Program'), (i) avoid creating gaps between key populations or habitat features (such as den trees or feeding trees), and (ii) mitigate unavoidable or existing gaps using ladder bridges, to minimise the risk that already small, disjointed populations are adversely affected. These recommendations could be embedded as 'conditions of approval' for projects subject to environmental regulations, such as the Environmental Protection and Biodiversity Conservation Act (1999).

We suspect that the camera set-up used here underestimated the crossing rates for arboreal marsupials, particularly for fast-moving, smaller-bodied species such as the Leadbeater's Possum, Agile Antechinus and Feathertail Glider. These species were often in frame for only a fraction of a second, making it difficult to identify species, or determine the behaviour and direction of travel. We also suspect that a large proportion of the 'false triggers' were caused by animals that were too fast to be recorded. For example, 95 crossings could not be confirmed by a second video; however, they were associated with an 'empty' video from the opposite side of the bridge at around the same time (within 1–3 min). This suggests that the empty videos were triggered by animal movement that was too fast to be captured. In some cases, this may have been due to poor alignment between the passive infrared sensor and the movement pathway (Moore *et al*. 2021). The limited ability to confirm crossings using multiple cameras, or detect species that cross at low rates should be carefully considered when monitoring the effectiveness of canopy bridges for small, fast-moving species.

Conclusion

Our work adds to a growing body of evidence that artificial canopy bridges facilitate the movement of arboreal mammals across roads. We show that canopy bridges are a useful tool for mitigating the impact of forest roads and firebreaks on the movement of a critically endangered possum. For Leadbeater's Possum there is some evidence that this movement would not have occurred in the absence of a bridge. However, wildlife crossing structures may provide only partial mitigation of the barrier effects of roads on wildlife movement (Olsson & Widen 2008; Van Manen *et al*. 2012; Soanes *et al*. 2013). For example, Soanes *et al*. (2013) found that while canopy bridges, glider poles and vegetated medians re-established wildlife movement across a major highway, movement was not restored to the same frequency as non-highway control sites. Further, the success of longer canopy bridges over forest gaps exceeding 100 m is yet to be evaluated, so the successful mitigation of narrow gaps should be generalised with caution and efforts that maintain natural canopy should be prioritised. Ladder bridges appear to be the better design choice for a wider range of arboreal marsupials as they offer greater stability and predator avoidance than single-rope designs. The multiple strands of rope within a ladder bridge also provide some design redundancy against damage or failure, as they are not dependent on a single strand. These factors are likely to become more important on larger, or high-traffic volume roads where animals are more exposed to disturbance. Future studies are required to assess the effect of narrow forest gaps and canopy bridges on movement for Leadbeater's Possums, with a focus on population-level effects and comparison to reference conditions (i.e. before data or control sites).

Acknowledgements

In memory of, and with thanks to, our colleague and friend Joanne Ainley. We acknowledge and thank the Traditional Owners of the lands on which this work was conducted, the Wurundjeri Woi Wurrung people of the Kulin Nation. We recognise that their sovereignty was never ceded and pay our respects to elders past and present. This work was supported by the Victorian Government Department for Environment, Land Water and Planning as part of the 'Strategic Firebreak Project' and the Baker Foundation (via the Australian Research Centre for Urban Ecology). We thank Dan Harley (Zoos Victoria), Lachie McBurney and David Lindenmayer (Australian National University) for advice on trapping protocols and location of possum colonies. Thanks to the editors and two anonymous reviewers for their comments on the manuscript. Tom Hodgson, Renee Mead and numerous other volunteers provided field assistance to locate colonies. Will Sowersby and Simone Harvey assisted with trapping. All work was completed in accordance with scientific licence no. 10004763 and University of Melbourne Animal Ethics Committee Approval no. 0810924.3. Open access publishing facilitated by The University of Melbourne, as part of the Wiley - The University of Melbourne agreement via the Council of Australian University Librarians.

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Supporting Information

Additional supporting information can be found in the following online files.

Video S1. Video of Tawny Frogmouth perching on canopy bridge.

Video S2. ideo of Feathertail Glider crossing single-rope canopy bridge.

Video S3. Video of Leadbeater's Possum crossing ladder-style canopy bridge.

Video S4. Video of Leadbeater's Possums fighting on canopy bridge.

Video S5. Video of Eastern Ringtail possum exiting single-rope bridge into adjacent vegetation.