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Culvert design and position in the landscape predict the presence of trawling bat culvert roosts in an urban environment

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Abstract

Trawling bats occur in urban environments globally and are found roosting in artificial structures near water such as bridges and culverts. Culverts are suitable dark, thermally stable and often humid environments, however knowledge on roost selection and availability of these artificial structures within urban environments are limited. The large-footed myotis (*Myotis macropus*) is a specialist trawling bat found roosting in culverts under roads in urban environments in Australia. We used an experimental design stratified by landscape variables and culvert attributes to identify roosting preferences to predict culvert roost potential distribution and quantify the availability of suitable culvert roosts for a trawling bat in the subtropical city of Brisbane, Australia. We completed seasonal surveys of 308 concrete culverts across the city, modelled the distribution of *M. macropus* roosts and then predicted available culvert habitat. The distribution of *M. macropus* roosts in concrete culverts is related to waterway density, distance to nearest large waterbody, vegetation cover and channel width at the landscape scale, and to the height and design of the culvert at the culvert scale. *Myotis macropus* preferred culverts taller than 1.2 m in height, and while a preference for box culverts was detected, both box and pipe designs were occupied. Culverts available for selection as roosts by *M. macropus* are limited in the city of Brisbane urban landscape. Disturbance to or loss of culvert roosts can have significant conservation implications to colonies of trawling bats roosting in culverts due to the limited availability of concrete culverts that provide suitable roost sites.

Keywords Subtropical urban environment · Culvert · Trawling Bat · *Myotis macropus* · Roosting habitat.

Introduction

Cities can support and contribute to the conservation of biodiversity, but urbanization can have a profound effect on the distribution, abundance, and composition of biodiversity in urban areas (Hahs et al. 2023). Urban environments are spatially heterogeneous landscapes that combine natural landscape features such as green and waterway networks, with anthropogenic features such as road networks and densely populated areas (Cadenasso et al. 2007). Understanding the spatial heterogeneity of urban environments is essential for effective urban planning and biodiversity conservation. The urban matrix of natural and anthropogenic features affects the distribution, abundance, and species composition of biodiversity in urban areas, yet our understanding of the processes structuring urban populations is limited.

In urban mammalian communities, bats (Chiroptera) are the most represented genera due to ecological and life history traits favouring adaptation to urban environments (Santini et al. 2019). Urban tolerant bat species are characterised by high mobility, flexibility in roost type, and opportunistic use of artificial roosting opportunities provided in urban areas (Jung and Threlfall 2018). This urban tolerance is generally associated with generalist species and their ability to adapt to available resources such as artificial habitat as roost sites (Wolf et al. 2022). Urban environments have reduced availability of natural roost sites such as cliffs, caves or trees. Urban bat populations are dependent on the availability of day roosts for survival, as these sites provide protection from predators and have stable microclimates to enable thermoregulation which influences reproductive success (Lewis 1995). Human constructions such as buildings,

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bridges and culverts can mimic the structural and functional properties of roosts found in cliffs, caves or trees, providing artificial roosting sites for urban bats (Russo and Ancillotto 2015). Many species of bats have been able to adapt to artificial roosting opportunities provided in urban environments, particularly bridges and culverts (Keeley and Tuttle 1999).

Trawling bats display urban-tolerant traits as they have both flexible roosting strategies - they occupy a variety of roost sites such as caves, trees, buildings, bridges, and culverts - and manoeuvrable flight developed for foraging over water (Campbell 2011; Jung and Threlfall 2018). Despite this mobility and flexibility, trawling bats occupy a narrow ecological niche due to their association with water, resulting in a higher risk of extinction due to habitat specialisation (Safi and Kerth 2004).Culverts are specialised roosting resources, as these structures are only located at set positions in the landscape (i.e., over water). Culverts are designed for drainage and enable water to flow under infrastructure. Although they vary in shape and design, they typically have reduced light, stable microclimates, and water in or around the culvert (Meierhofer et al. 2019). All of these factors create suitable roosting environments for bats, particularly trawling bats given their proximity to foraging resources (Keeley and Tuttle 1999).

Although culverts are abundant in urban environments, bats display selection preferences among these artificial roosts with evidence of a preference for roosting in box culverts taller than 1.5 m, and for longer (>100 m) culverts (Walker et al. 1996; Schulz 1998; Keeley and Tuttle 1999; Bender et al. 2010; Meierhofer et al. 2019). Taller culverts may be easier for a bat to detect and offer increased protection from predators (Campbell 2009), while longer culverts may provide increased roosting potential due to greater surface area available to bats (Keeley and Tuttle 1999). Whilst evidence exists for culvert roost selection preferences, little is known about the availability of roost culverts in an urban environment to quantify both the conservation value, and the potential impact of the loss, of these roosts. The use of culvert roosts within urban areas increases the risk of human-wildlife conflict associated with necessary culvert repairs, maintenance or upgrades, increasing the likelihood of displacement and disruption to social groups if colonies are excluded from culvert roost sites or roost sites are removed (Russo and Ancillotto 2015). The loss of roosting resources can decrease colony size, increase energy expenditure and affect overall reproductive success (Brigham and Fenton 1986).

For effective management and conservation of urban culvert roosts, research is needed to identify urban culvert roost selection preference and availability of this specialised roost type within an urban environment. The aim of this study was to identify culvert roost selection by a trawling bat, the large-footed myotis *Myotis macropus* in a subtropical urban environment and to quantify the availability of this roost type across the city of Brisbane, Australia. *Myotis macropus* is the only trawling species in Australia, and like other trawling bats, roosts within 500 m of water in bridges, tunnels, jetties, road culverts and stormwater drains (Campbell 2011; Gonsalves and Law 2017; Gorecki et al. 2020). We used a stratified sampling and distribution modelling approach to identify the landscape variables and culvert attributes that make a culvert suitable for roosting for this trawling bat. We then used the model to predict the distribution of culverts potentially suitable for roosting across the subtropical city of Brisbane. Specifically, we aimed to (1) identify landscape and culvert attributes that predict culverts suitability for roosting, and to (2) identify the availability of culvert roost habitat, to quantify the availability of this resource to an urban trawling bat.

Materials and methods

Study area

The study was conducted in the city of Brisbane in southeast Queensland, Australia (Fig. 1). The Brisbane City Council (BCC) area covers 117,000 hectares and is characterised by a subtropical climate. The urban landscape of BCC is dominated by residential housing, industrial and commercial areas covering 62% of the local government area (LGA) (ABARES 2016). Water covers 6% of the LGA due to the meandering Brisbane River and its tributaries, as well as several large waterbodies that include water supply reservoirs and dams.

Stratified design

An asset database identifying culverts in the study area was obtained from BCC and included a total of 2666 concrete culverts located on council owned roads, excluding highways. The database provided unique asset identification codes for each culvert and information about height, width, length, number of barrels, construction age, material, design (box or pipe) and location. This study focused on concrete culverts as insufficient replicates of culverts constructed in different materials (steel = 18, brick = 2, cast iron = 6 and timber = 1) were available.

Sampling was stratified according to the method of Maggini et al. (2002) using landscape variables and culvert attributes that most likely influence their suitability as roosts. The stratifying factors were land use, waterway permanency, culvert design and culvert size (Fig. 1; Supplementary material Table 1). Bat species assemblage and

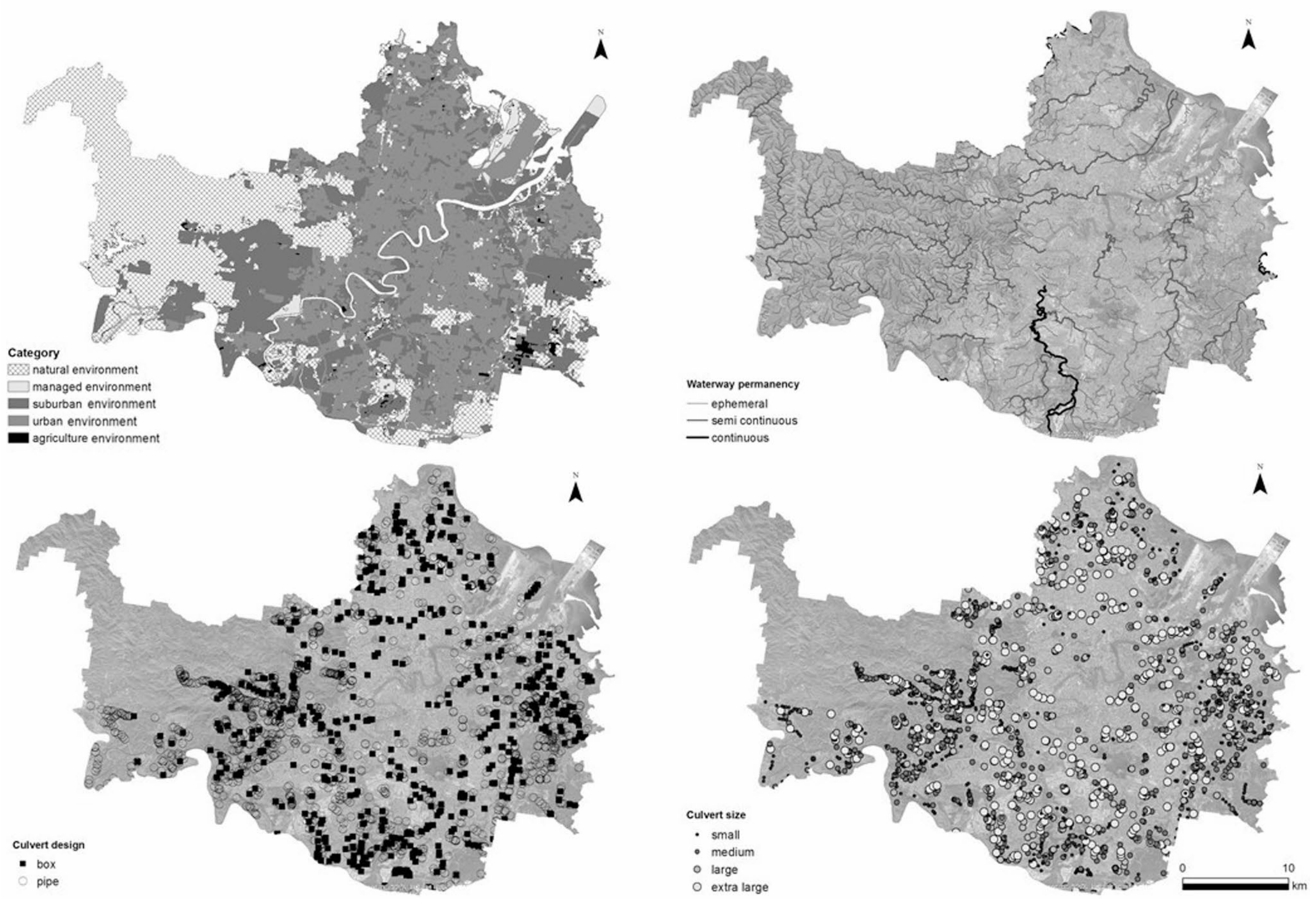

Fig. 1 Variables used to stratify the sampling of *Myotis macropus* and relative distribution across Brisbane City Council: (**a**) land use; (**b**) waterway permanency; (**c**) culvert design; (**d**) culvert size

distribution is strongly influenced by landscape structure (Norberg and Rayner 1987) so land use was used as a proxy for landscape structure in this study. *Myotis macropus* has a strong association with waterways and large water bodies (Barclay et al. 2000; Campbell 2009), therefore waterway permanency was used as an indicator of water availability and permanency at the site. Although evidence exists for bat roosts in culverts > 1.5 m in height, the influence of design (shape) and size on culvert suitability as a roost site has not been assessed in previous studies.

Land use was derived from the Australian Land Use and Management Classification GIS file (ABARES 2016). A total of five broad categories were defined: (i) natural, (ii) managed, (iii) agricultural, (iv) suburban, and (v) urban environment (Table 1. Waterway permanency was derived from stream order classifications provided in the Queensland Drainage 25k GIS file (DERM 2010). Three waterway permanency categories were defined: (i) ephemeral, (ii) semi continuous and (iii) continuous (Table 1). Estuarine waterways were not included in this study. Culvert design was based on the shape of the culvert and comprised two categories: (i) box (square or rectangular), and (ii) pipe (circular). Culvert size categories were derived from the diameter of culverts and were classified into four categories: (i) small, (ii) medium, (iii) large and (iv) extra-large (Table 1).

Field sampling

Field sampling was conducted during the austral summer of 2017 and 2018 (December to April, October to November, respectively), and winter of 2018 (May to September). Each culvert was surveyed for the presence of *M. macropus* during the day, once in summer and once in winter. A headlamp was used to light the space within the culvert and inspect structural features such as lift holes and structural deformities such as cracks and crevices. An endoscopic camera was used to inspect deep or partially blocked structural deformities. A maximum of 20 min was spent searching each structure to standardise search effort. If *M. macropus* was present, the number of bats was recorded, and the culvert was defined as occupied. If no evidence of bat occupancy was present or if evidence of bat occupancy was present (e.g. guano, staining) but no bats were observed, the culvert

Table 1 Descriptions of culvert attributes and landscape variables used for the stratification of the sampling (marked with an asterisk *) and the modelling of culvert suitability for roosting by *Myotis macropus* in two models: (1) ecological model and (2) culvert structural model

Variable	Source	Description	Model
Land Use*	GIS-derived from ABARES 2016	Land use category- (i) **natural**: conservation areas and native vegetation, (ii) **managed**: production landscapes with structured vegetation and low intensity uses, (iii) **agricultural**: production landscapes with limited structural vegetation and high intensity uses, (iv) **suburban**: low-medium density urban areas and industrial areas with modified natural areas and (v) **urban environment**: high density urban areas and commercial areas with limited natural areas.	Ecology, culvert
Waterway permanency*	GIS-derived from Queensland Drainage 25k	(i) **ephemeral**: stream orders 1–2, streams that may have either a continuous or a discontinuous channel whereby intermittent base flows occur episodically after rain but generally there is no permanent water source, (ii) **semi continuous**: stream orders 3–4 with continuous base flows or semi-permanent pools that are not dependent on episodic rainfall and (iii) **continuous**: stream orders 5–6 with a continuous channel with well-defined banks and floodplain with permanent, or semi-permanent, base flows	Ecology
Design*	asset database	Shape of the culvert- (i) **box** culverts: square or rectangular tunnels and (ii) **pipe** culverts: circular pipes.	Ecology, culvert
Size*	asset database	Culvert size- (i) **small**: <500 mm, (ii) **medium**: 500<=x<1000 mm, (iii) **large**: 1000<=x<1500 mm and (iv) **extra-large**: =>1500 mm.	Ecology, culvert
Height*	asset database	Height of culvert (mm)	Ecology, culvert
Width	asset database	Width of culvert (mm)	Ecology, culvert
Length	asset database	Length of culvert (m)	Ecology, culvert
Barrels	asset database	Number of barrels (sections) at a culvert	Ecology, culvert
Channel Width	Field	Bankfull width of waterway (m)	Ecology
Channel Depth	Field	Bankfull depth of waterway (m)	Ecology
Stream order	GIS-derived from Queensland Drainage 25k	Stream order culvert is located on, categorical variable derived from stream order classifications (1–5)	Ecology, culvert
VegHeight	Field	Height of ecologically dominant layer (EDL) over 25 m transect centred on culvert	Ecology
VegCover	Field	Projected foliage cover over a 25 m transect centred on culvert	Ecology
NearestLight	Field	Distance from centre of culvert to nearest streetlight (m)	Ecology
RSdensity	GIS-derived	Density of road structures (culverts and bridges) within 1, 5, 10, 15 km (number of structures per square kilometre)	Ecology
wwaydensity	GIS-derived	Density of waterways within 1, 5, 10, 15 km (length of waterways (km) per square kilometres)	Ecology
NearestSmallWater	GIS-derived	Distance to small waterbody (<625 sq m in size)	Ecology
NearestLargeWater	GIS-derived	Distance to large waterbody (=>625 sq m in size)	Ecology
Northness	GIS-derived	Orientation of culvert along a south-north gradient (-1=south, 1=north)	Ecology
Eastness	GIS-derived	Orientation of culvert along a west-east gradient (-1=west, 1=east)	Ecology
PercentVeg	GIS-derived	Percent cover of vegetation in each 25 m pixel	Ecology

was defined as unoccupied due to the uncertainty of which species may have occupied the culvert.

Culvert orientation was recorded by taking a compass bearing at the upstream end of the culvert and converting it into west-east (eastness) and south-north (northness) gradients. Culvert orientation was recorded to test for a preference in orientation as bat roosts are often orientated towards the east to maximise solar exposure to provide suitable microclimates for unfurred pups due to the warming effect of solar radiation (Mering and Chambers 2014). Distance to nearest streetlight was recorded due to evidence that artificial lighting at night (ALAN) has significant, negative impacts on the movement of bats in urban environments (Laforge et al. 2019; Russo et al. 2019). Channel width and depth was included to test for preferences in waterway size (Anderson et al. 2005) and vegetation height and cover was included to test for preferences in vegetation structure. Surveys were carried out under permits issued by Queensland Department of Environment and Science (Scientific Purposes Permit WA0001898) and Queensland University of Technology Animal Ethics (AEC1700000540) and Biosafety Committees (1700000368).

GIS-derived variables

We derived additional GIS-based landscape variables from different sources using ArcGIS v10.5 (Table 1) to be used for the modelling. The density of potential available roosting habitat in the form of road structures such as culvert and bridges within 1, 5, 10 and 15 km (search radius from each culvert) was calculated using the BCC asset database (Table 1: *RSdensity*). The density of potential foraging resources in the form of waterways (*wwaydensity*) at 1, 5, 10 and 15 km (search radius from each culvert) was calculated using the GIS file Queensland Drainage 25k (Management 2010). Distance from each culvert to the nearest small waterbody (size < 625 m^2; *NearestSmallWater*) and large waterbody (> 625 m^2; *NearestLargeWater*) were calculated using the spatial layers Small Water Bodies and Large Water Bodies, accessed through the Queensland Government QSpatial portal (QSpatial 2017). A layer of percent vegetation cover was created by merging the Queensland Regional Ecosystem spatial layer - which identifies polygons of remnant vegetation and high-value regrowth, BCC's significant landscape tree layer - which identifies mature landscape trees, and BCC's parklands layer -which identifies council owned parks and green spaces. This resulted in a single spatial layer of polygons identifying patches of all vegetation within the study area.

Statistical modelling

Collinearity between predictor variables was investigated prior to modelling. When a correlation above 0.7 was detected, univariate models were fitted for each of the correlated variables and the variable that had the lowest contribution was removed. Response to variables calculated at different scales (road structure density, waterway density) was also modelled separately to identify the relevant scale for each predictor. Road structure density at 10 km and waterway density at 5 km had the strongest relationships with the presence of a roost and were further used in the modelling.

We used Generalised Additive Models (GAM) (Hastie and Tibshirani 1990) to investigate relationships between the presence of a roost in a concrete culvert and landscape variables and culvert attributes. By using smooth functions, GAMs provide a flexible method to explore without restrictions the shape of the relationship between the predictors and the response variable. Models were built in R version v.3.4.2 (R Development Core Team 2011) using the multiple generalised cross-validation 'mgcv' package (Wood 2007). The presence/absence (binomial distribution) of a roost in a culvert was modelled using penalised regression splines with smoothing parameters selected by Unbiased Risk Estimator for each variable.

Two different models were defined. The first model is 'ecological' describing *M. macropus* roost selection and was fitted using landscape variables and culvert attributes that were used to stratify the sampling, GIS-derived or collected in the field. The ecological model was developed to align with the type of spatial data that is available during the planning process when assessments of biodiversity are being undertaken on transport networks. The second model is 'culvert structural' calibrated using only culvert attributes available from the asset database (height, width, length, number of barrels, design and stream order; Table 1 and aimed at identifying characteristics of culverts selected as roost sites. The culvert model was developed to determine if a roost could be predicted to occur for the instances when ecological data may not be available i.e. as part of a risk assessment process for maintenance crews arriving at a culvert to undertake repair work.

The models were selected using the backward selection strategy and the lowest Akaike's Information Criterion (AIC) (Akaike 1973; Wood 2007). The gam.check function in the 'mgcv' package was used to inspect the residual plot vs. fitted values, the Quantile-Quantile plot (QQ-plot), the residual plot against the original explanatory variables, and the histogram of residuals. A three-dimensional perspective plot was generated to assess interactions between variables retained in the model using the vis.gam function. Models were evaluated using the area under the curve (AUC) of a Receiver Operating Characteristic (ROC) plot (Fielding and Bell 1997). Model performance was further evaluated using the correlation between model predictions and presence/absence of *M. macropus* roosts (observed data).

Predicted availability of culvert roosts

We used the final 'culvert structural' model and the full BCC asset database to identify the spatial distribution of potentially suitable culverts for roosting across Brisbane. We used the culvert model to focus on structural attributes of culverts rather than landscape attributes that are subject to change i.e. vegetation cover. To do so, we first used the predict.gam function in the 'mgcv' package (Wood 2007), the culvert structural model and the full BCC database to generate the probability of occurrence of *M. macropus* in each culvert. Using the 'PresenceAbsence' package (Freeman and Moisen 2008), we then compared the predicted probability of occurrence to the observed presence/absence to determine the optimal threshold to convert all probabilities. We tested different methods (MaxKappa, PredPrev = Obs, MaxSensSpec, ReqSens) to determine the optimal threshold for the conversion, and compared them based on confusion matrices, Kappa values, and predicted prevalence (Freeman and Moisen 2008). Predicted probabilities equal to or above the threshold were classified as presences, while values below the threshold were classified as absences.

Results

***Myotis macropus*roost distribution**.

Out of the 308 concrete culverts inspected, 23 *M. macropus* roosts were identified over the two seasonal visits (Fig. 2). Colony sizes displayed seasonal variation with larger colonies identified in summer. A total of 14 *M. macropus* roost sites were located in summer with a mean colony size of 15 individuals (range 1–65), while 14 roosts with a mean colony size of 8 (range 1–34) were identified in winter. Due to the low number of roosts detected, data for both seasons was pooled to proceed with presence-absence modelling.

Ecological model

The final model (Model 3, Table 2) was selected for lowest AIC, highest percentage of explained variance (77.60%), highest AUC value (0.99) and highest correlation between model predictions and observed data (0.85). The final model identified six significant predictors, including two variables associated with culvert attributes - culvert height and pipe

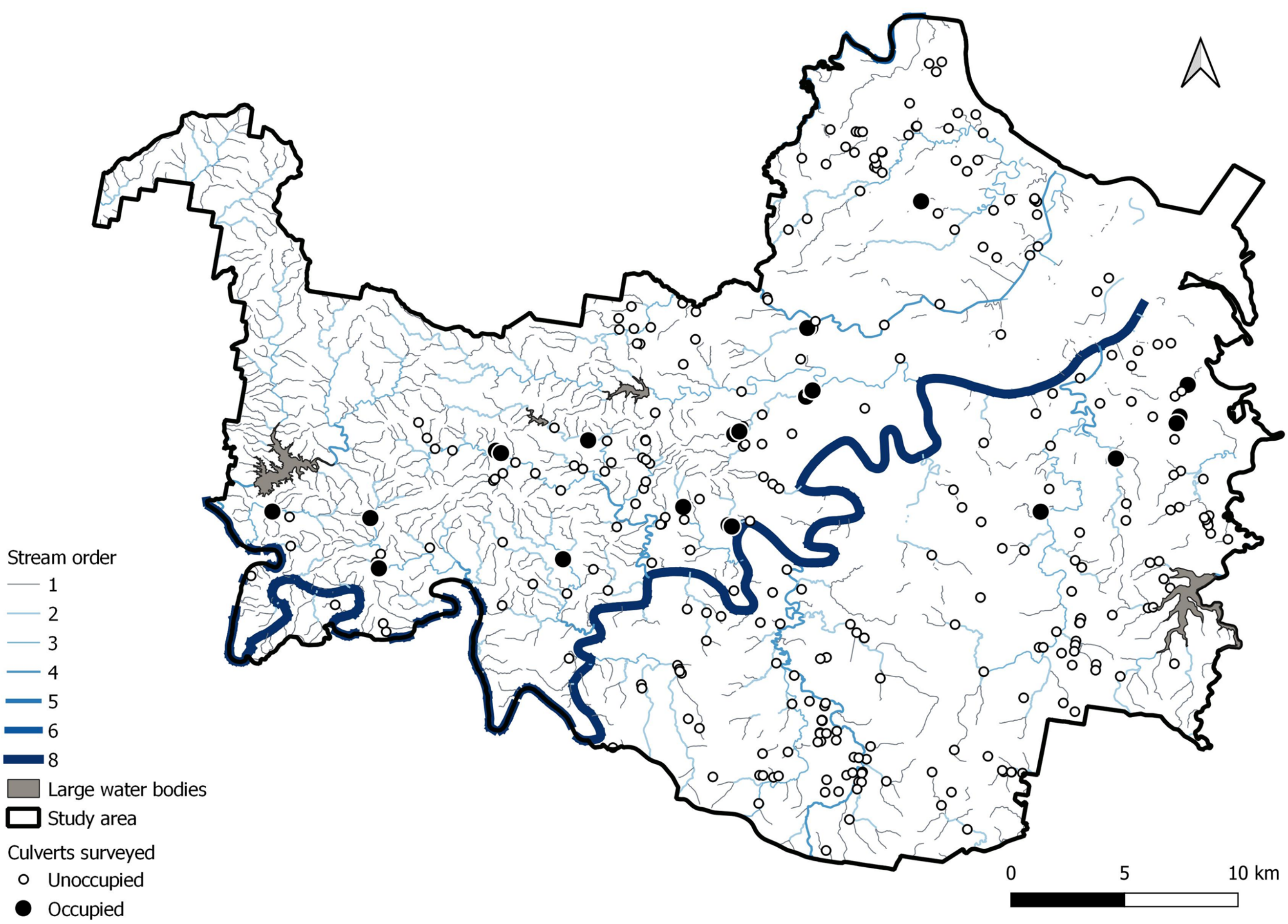

Fig. 2 Distribution of culverts surveyed for the presence of *Myotis macropus* roosts

Table 2 Three GAM models describing the relationship between the presence of a *Myotis macropus* roost in a concrete culvert and predictive landscape variables and culvert attributes. Model 3 shows the best fit

Model and variables	Estimate/edf	*p*-value	Sig.	Dev. explained (%)	AIC	AUC	Cor
Model 1				**65.00**	**75.13**	**0.98**	**0.76**
Intercept	-9.33	0.00018	***				
Box	2.05	0.02061	*				
Height	2.22	0.00814	**				
ChannelWidth	2.85	0.03634	*				
Waterway5km	1.94	0.00540	**				
NearestLWater	2.74	0.01929	*				
Model 2				**66.30**	**72.17**	**0.98**	**0.76**
Intercept	-7.98	0.000406	***				
StreamOrder5	2.16	0.000264	***				
Height	2.12	0.015984	*				
VegetationCover	3.00	0.001151	**				
NearestLWater	1.00	0.049621	*				
RoadStructure10km	1.00	0.007464	**				
Waterway5km	2.06	0.000264	***				
Model 3				**77.60**	**62.85**	**0.99**	**0.85**
Intercept	-11.026	0.00840	**				
Design (pipe)	-2.977	0.02710	*				
Height	2.390	0.00145	**				
ChannelWidth	2.362	0.04550	*				
VegetationCover	3.000	0.01135	*				
NearestLWater	2.975	0.00854	**				
Waterway5km	2.141	0.00387	**				

design; and four ‘landscape’ variables - waterway density at 5 km, distance to nearest large waterbody, vegetation cover and channel width (Table 2).

Culvert height proved to be the most significant predictor ($p=0.001$) of a roost. *Myotis macropus* displayed a preference for taller culverts with the spline plot showing an increasing probability of a roost as culvert height increases up to an optimum of 2.5 m (Supplementary material Fig. 1). Roosts were only found in sampled culverts of 1.2–3.0 m in height. Roosts were found in 6 pipe culverts and 17 box culverts, and the final model identified a negative relationship with pipe culverts ($p=0.027$) suggesting *M. macropus* prefers box culverts. However, culverts over 1.2 m in height were typically box shaped and located on higher order streams (Fig. 3).

Channel width was a significant predictor of a roost ($p=0.045$) with an increasing probability of the presence of a roost associated with channels up to 10 m wide and with an optimum around 7 m. After this value, the relationship seems to become negative, although there is a large error associated with the estimate in this part of the curve (Supplementary material Fig. 1). The probability of a roost occurring in a culvert increases with increasing waterway density within 5 km of the roost ($p=0.003$) and with increasing distance from the nearest large waterbody ($p=0.008$) (Supplementary material Fig. 1). Note however, that large waterbodies (reservoirs, dams) are located high in the catchment (Fig. 1) and culverts closest to large waterbodies are smaller than culverts that are located further away from large waterbodies (Supplementary material Fig. 2).

Roosts are associated with a higher degree of vegetation cover at the culvert scale but not at the landscape scale, since the final model retains the predictor related to the amount of vegetation available immediately surrounding a culvert ($p=0.01$) rather than the vegetation in the 25 m pixel (projected foliage cover).

Culvert structural model

The best structural model (model 3) was selected for having the lowest AIC (95.84), highest amount of variance explained (46.10%) and an AUC of 0.94, indicating excellent discriminatory power between culverts with and without roosts. Model 3 also had the highest correlation (0.60) between observed and predicted values, showing better alignment between predictions and data than Models 1 (0.51) or 2 (0.59). (Table 3 and Supplementary material Fig. 3).Culvert height proved once again to be a strong predictor of a roost ($p<0.001$). Stream order was the second significant variable retained in the final model with *M. macropus* showing a preference for stream order two ($p=0.03$) and a slight tendance for stream order five although this was not significant ($p=0.07$). The model retained pipe culverts as a negative predictor although not significantly (Design

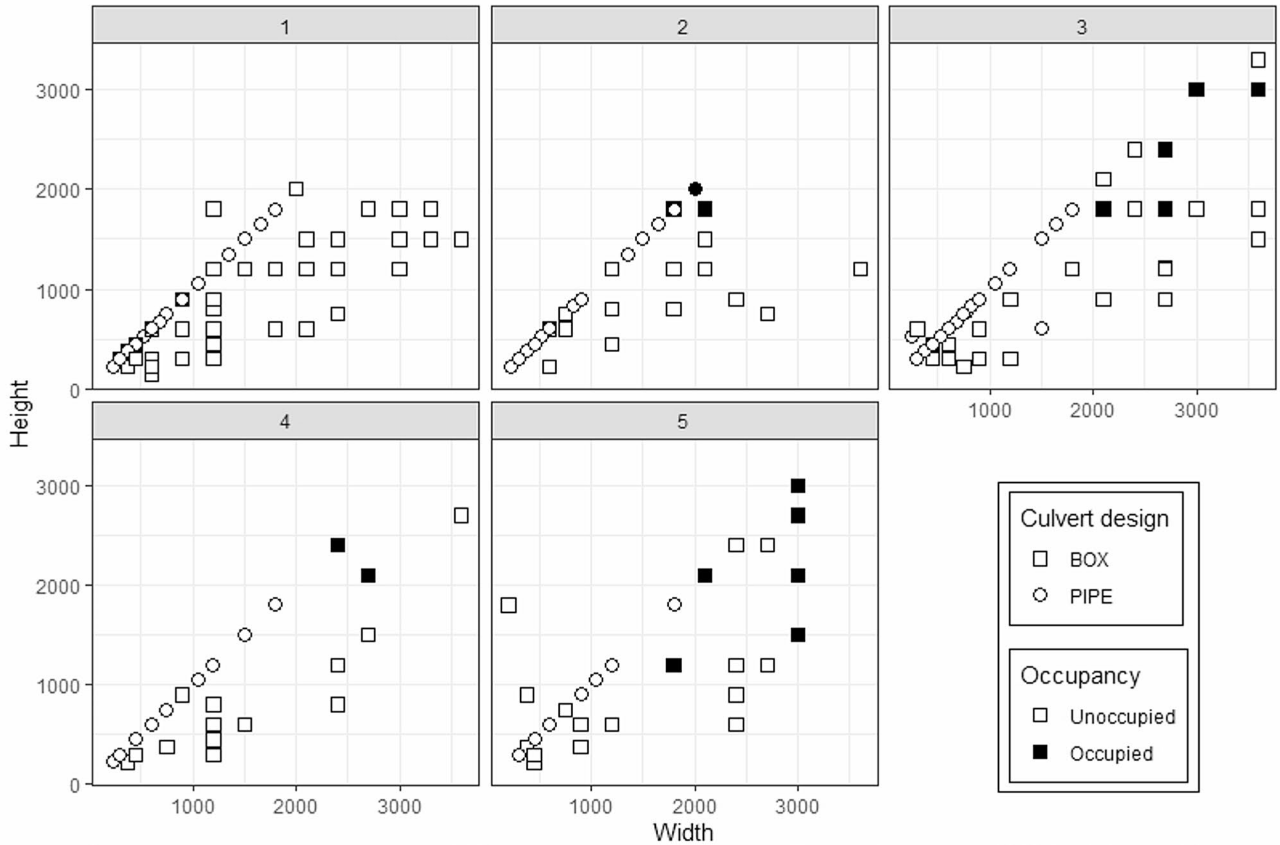

Fig. 3 Culvert height (mm) and culvert width (mm) increases with increasing stream order (panels 1–5); culverts occupied by *Myotis macropus* > 1.2 m in height are more available on stream orders 3–5

Table 3 GAM models describing the relationship between the presence of a *Myotis macropus* roost in a concrete culvert and culvert attributes relative to stream order

Model and variables	Estimate/edf	*p*-value	Sig.	Dev. explained (%)	AIC	AUC	Cor
Model 1				**38.90**	**96.17**	**0.92**	**0.51**
Intercept	-4.79	0.000000136	***				
Height	1.97	0.0000588	***				
Model 2				**44.40**	**96.14**	**0.94**	**0.59**
Intercept	-6.01	0.000000535	***				
Height	2.00	0.000214	***				
StreamOrder2	1.84	0.0439	*				
StreamOrder3	0.50	0.6112					
StreamOrder4	1.69	0.1261					
StreamOrder5	1.86	0.0574					
Model 3				**46.10**	**95.84**	**0.94**	**0.60**
Intercept	-5.89	0.0000132	***				
Height	2.102	0.00102	**				
Design (pipe)	-0.946	0.1588					
StreamOrder2	2.0199	0.0302	*				
StreamOrder3	0.3948	0.6932					
StreamOrder4	1.7098	0.1327					
StreamOrder5	1.7744	0.0750	.				

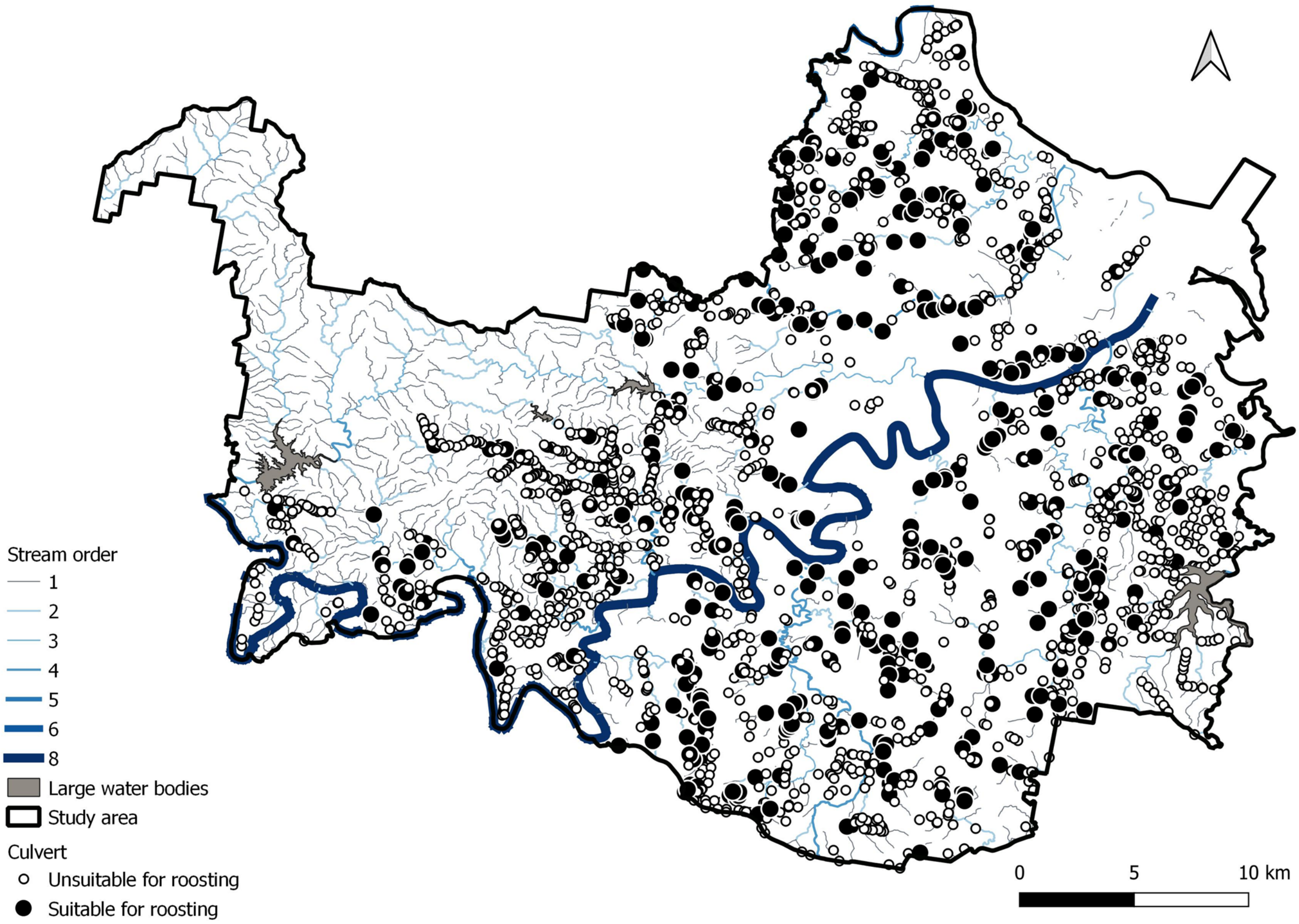

Fig. 4 Map of potentially suitable culverts for roosting by *Myotis macropus* across Brisbane

(pipe), $p=0.15$), suggesting *M. macropus* either avoid pipe culverts or prefer box culverts. Model 3 demonstrates the best balance between statistical performance and ecological relevance. Despite including one non-significant predictor (design) in consideration of its importance in defining culvert's structure, it achieves stronger predictive accuracy and better reflects the multifactorial nature of *M. macropus* roost selection.

Predicted availability of culvert roosts across BCC

An optimal threshold of 0.32 was identified using the MaxKappa method for converting the predicted probabilities of occurrence from the culvert structural model. MaxKappa was the method that gave the best results: highest Kappa value (0.59) and a predicted prevalence (0.07) that was closest to the observed prevalence (0.06). The assessment of predicted availability of culvert roosts across BCC shows that although a multitude of culverts are available across the study area, culverts that are potentially suitable for roosting by *M. macropus* are limited (146 out of 2666 concrete culverts, i.e. 5.5%; Fig. 4). The limited availability of suitable culverts is driven by a reduced number of tall and box culverts. Within BCC only 754 culverts (28.0%) are higher than 1.2 m and only 882 (33.1%) are boxes. These structural requirements combined with water requirements (stream order) result in a very restricted number of suitable culverts.

Discussion

This study is the first to explore culvert distribution across a city and to assess their suitability for roosting by a trawling bat using a modelling framework. We modelled roost preferences by the trawling bat *M. macropus* in an urban environment using culvert attributes and landscape variables and showed that culverts suitable for roosting are a limited resource due to the required combination of culvert structure and stream order (i.e. 5.5% of culverts). The model was then used to predict the distribution of culverts potentially suitable for roosting across the city. The use of a modelling framework based on a stratified experimental design demonstrates the advantage of incorporating predictive modelling into ecological assessments. The colony sizes for *M. macropus* found in concrete culverts in our study is similar to those recorded both in natural roosts and in other artificial roosts. We found colony sizes ranging from 1 to 65 (av = 15.2) in summer and 1–34 (av = 8.3) in winter. As a comparison, 40–60 *M. macropus* were recorded in a tree roost (Dwyer 1970), 30 individuals in a cave roost (Campbell 2009), 50 in a jetty, (Gonsalves and Law 2017) and 21 in an abandoned rail tunnel (Barclay et al. 2000) in previous studies.

Culvert attributes that determine roost suitability

Culvert height was the strongest predictor of the presence of a roost. Roosts were only located in culverts 1.2–3.0 m in height, which is the size of culvert roosts reported by other researchers (Walker et al. 1996; Keeley and Tuttle 1999; Meierhofer et al. 2019). Taller culverts may be easier for a bat to find (Meierhofer et al. 2019) and tall culverts may also provide foraging environments with increased protection from predators. Tall culverts elevate the foraging space above ground level. This could provide bats with a height advantage, making it more challenging for ground-based predators to reach them. Bats may take advantage of the vertical space to navigate and hunt insects without being as easily accessible to ground-dwelling threats. *Myotis macropus* roosting in a tunnel was reported emerging from crevices twenty minutes earlier than conspecifics in nearby tree cavities yet did not exit the tunnel until a similar time after sunset (Campbell 2009). These twenty minutes of safe foraging time within the tunnel provided tunnel roosting *M. macropus* with an opportunity to forage while protected from aerial predators (Campbell 2009). Tall culverts would provide similar predator free protection to urban *M. macropus* and may be a contributing factor to the selection of culverts.

Our results indicate that culvert design was also a significant predictor of the presence of a roost, although this could also be explained by the height of a culvert. Culverts over 1.2 m in height were boxes located on higher order streams. Box culverts were taller than pipe culverts so the preference for culvert design is likely driven by the height of the culvert, rather than the shape. Similarly, Schulz (1998) did not find a relationship between the presence of bats and ceiling roundness but did find a significant positive relationship with culvert height. Our study did not find the length of the culvert was a significant predictor of a *M. macropus* roost. Several studies have identified culvert length as a significant driver of roost selection in culverts, suggesting that longer culverts increase roosting potential by increasing the surface area available to bats. We did not find that *M. macropus* preferred longer culverts nor avoided short culverts. Our finding is supported by other studies reporting on roosts in culverts < 100 m (Bender et al. 2010; Hice et al. 2004; Monadjem et al. 2015). Therefore, we do not advise the use of culvert length as a predictor of the presence of a bat roost in targeted culvert surveys and recommend all culverts over 1.2 m in height are inspected for bat occupancy prior to any maintenance or construction works to a concrete culvert.

Landscape variables surrounding culvert roosts

Roosts in culverts were located at lower elevation in the catchment, on wider waterways which require larger culverts. We found an increasing probability of the presence of a roost associated with channels up to 10 m wide and a negative relationship between culvert roosts and proximity to large waterbodies and this can be explained by the location of taller culverts in the landscape, relative to large waterbodies. Tall culverts are inherently located at increasing distances from water supply sources, on wider waterways. This result could also indicate that in our study, urban *M. macropus* populations are not reliant on large waterbodies as foraging sites. Tall culverts are located further down the catchment in landscapes with a higher density of waterways which could provide *M. macropus* with sufficient foraging resources, so they are not required to commute to large water bodies. *Myotis macropus* are more likely to be recorded foraging on stream orders 4–6 which occur at lower elevation and contain large, smooth pools with limited riffle zones (Anderson et al. 2005). This habitat preference is consistent with habitat use by other trawling bats such as Daubenton's bat (*Myotis daubentonii*), the pond bat (*Myotis dasycneme*) and long fingered bat (*Myotis capaccinii*). Large, elongate pools with smooth surfaces are preferred foraging grounds for trawling bats due to high insect activity and reduced clutter associated with rough water surfaces that interfere with echolocation (Warren et al. 2000; Lintott et al. 2015; Todd and Williamson 2019). The distribution of *M. daubentonii* was associated with a preference for smooth water sections of the river, located on wide rivers at lower altitudes, with well-structured riparian forests (López-Baucells et al. 2017; Todd and Williamson 2019). Similarly, *M. dasycneme* displayed an affinity for medium to large waterways and large lowland ponds (Van De Sijpe et al. 2004)d *capaccinii* selects large rivers with smooth surfaces that do not impede prey detection by echolocation (Almenar et al. 2006).

Our finding that percent vegetation cover at a landscape scale is not a significant predictor of a roost reflects the importance of riparian corridors to a trawling bat, rather than patches of vegetation as also reported for M. *daubentonii* (López-Baucells et al. 2017). Radio-tracking of *M. macropus* identified a preference for green and blue space associated with the recreation land use type at both the landscape and home range scale (Gorecki et al. 2024). Tracked bats used waterways and riparian areas, as well as parkland, sportsgrounds and other green space adjacent to waterways. The importance of riparian corridors to trawling bats in urban environments has been well documented with studies demonstrating both, higher bat activity within riparian habitats compared to adjacent residential areas and the value of these linear landscape features in providing functional landscape connectivity to specialist riparian species (Lintott et al. 2015; Russo and Ancillotto 2015).

We measured distance between each culvert and the nearest streetlight expecting to find a negative relationship on culvert selection due to the growing evidence that many species of bats are negatively impacted by the effects of ALAN on landscape connectivity (Laforge et al. 2019). However, we found no significant effect of distance to nearest streetlight on roost selection within culverts and some culvert roosts had streetlights located directly at the entrance. Data is lacking globally on the impacts of ALAN on roosting and entrances to hibernacula (Voigt et al. 2021). We postulate our finding reflects the limited availability of roosts in this urban environment. Our modelling identified that potential culvert roosting habitat was limited across Brisbane. Natural roosts like cavities, fissures and hollows associated with mature trees are also a limited resource in urban environments where mature trees are sparse (Le Roux et al. 2014). The limited availability of both natural and artificial roosts may result in urban bats selecting roosts despite being affected by light (Russo and Ancillotto 2015). Artificial light may delay emergence from roosts and may cause bats to miss peak insect abundance, reducing foraging time (Stone et al. 2015), although tunnels and culverts may provide a temporary opportunity for bats to forage within the structure (Campbell 2009). The impact of reduced foraging times on bat fitness can have significant consequences for the health and survival of bat populations. Foraging is crucial for a bat to acquire sufficient energy and nutrients for survival, reproduction, and overall fitness and the impacts of ALAN on roost emergence times needs to be assessed (Stone et al. 2015).

Trawling bats display varying responses to ALAN with higher sensitivity to foraging habitat than commuting corridors, with our result suggesting tolerance of light at culvert roost entrances. Trawling bats display a negative response to ALAN with reduced foraging and drinking activity at lit sites (Russo et al. 2017, 2019; Laforge et al. 2019; Voigt et al. 2021; Hooker et al. 2022), and peaks of activity after lights are turned off (Laforge et al. 2019; Hooker et al. 2022). This response may reflect avoidance of lit areas due to the slow speed trawling bats move as they forage, resulting in an increased predation risk at illuminated areas (Laforge et al. 2019). In contrast, trawling bats continue using lit commuting corridors (Spoelstra et al. 2018; Voigt et al. 2021; Hooker et al. 2022), likely due to faster, direct flight associated with movement between foraging grounds (Barclay et al. 2000).

Implications to the management of culvert roosts and urban trawling bats

Despite the availability of 2666 concrete culverts across our study area, only 146 (5.5%) met the preferred culvert characteristics within the optimal landscape position to provide potential culvert roosting habitat. Our study highlights how limited culvert roost sites are in an urban environment and suggests that culverts containing bat colonies may be critical sites for urban bat populations and their conservation. Culvert roosts are limited at a landscape scale due to the rarity of required combinations of culvert attributes and landscape variables. Tall culverts provide suitable roost sites for urban *M. macropus* populations, helping this species to persist in a highly modified landscape. The limited availability of tall culverts can be compared to the scarcity of hollow bearing trees for both hollow-roosting bats (Rhodes and Wardell-Johnson 2006) and birds (Davis et al. 2013) in urban environments. Culverts > 1.2 m in height, on stream orders 2–5 and located in landscapes with medium to high densities of waterways are critical urban habitat for *M. macropus* and can be considered sites of high conservation value. Culvert roosts are also limited at a roost site scale due to the limited availability of microhabitat such as lift holes and crevices found within urban culverts (Gorecki et al. 2020), and contribute to sympatric bat species sharing limited roosting resources (Kwak et al. 2022).

The discovery of culvert roosts being a limited resource has implications for the management of culvert roosts. Disturbance to a roost culvert can displace an urban bat population since culverts suitable for roosting are not readily available and natural roost sites are scarce in urban environments. Roost disturbance involving roost exclusion could be a significant conservation issue to urban bat populations as reproductive success can be reduced (Brigham and Fenton 1986). This impact is magnified if a roost disturbance or exclusion occurs in the breeding season. Culverts suitable for roosting are a limited resource in Brisbane and this study indicates that displaced culvert roosting bats may not have many suitable roost sites available to disperse to after disturbance or exclusion.

Our study demonstrates that culvert roosts occur in a predictable type of culvert, and these types of culverts should be surveyed before they are disturbed due to road works or general maintenance activities which can impact on urban culvert roosting trawling bat colonies. Additionally, our study identified that the type of culvert available for bats to select as a roost are rare in the landscape, so disturbing culvert roosts is a high risk to the viability of urban trawling bat colonies roosting in these types of culverts. We recommend that all culverts are inspected prior to any disturbance, and culverts > 1.2 m in height should be prioritised for inspection for use by bats prior to any construction or maintenance works. If bat occupancy is identified, confirmation of alternative habitat must be obtained prior to disturbance to an urban culvert roost. The identification and protection of roosts in urban areas is vital for the persistence of trawling bats in urban environments.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval Surveys were carried out under permits issued by Queensland Department of Environment and Science (Scientific Purposes Permit WA0001898) and Queensland University of Technology Animal Ethics (AEC1700000540) and Biosafety Committees (1700000368).

Consent tp participate/for publication No human subjects involved in this study.

Competing interests The authors declare no competing interests.

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