



University of  
Southern  
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## Monitoring and management of Yakka Skinks and Squatter Pigeons in the Galilee Basin

Galilee Basin Conservation & Research Fund

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Bottom – Squatter pigeon, photo credit Ged Tranter.

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# Background

Galilee Basin Biodiversity Company on behalf of the Galilee Basin Conservation & Research Fund engaged University of Southern Queensland (UniSQ) to undertake a research project in accordance with the Carmichael Conservation and Research Program.

The project titled “Monitoring and management of Yakka Skinks and Squatter Pigeons in the Galilee Basin” aims to undertake large-scale and small-scale experimental trials investigating the effects of grazing, fire and invasive species on Yakka Skinks and Squatter Pigeons; and regional surveys/monitoring for Yakka Skinks and Squatter Pigeons.

This research will provide key information on two of the Galilee Basin Conservation and Research Fund’s target MNES, quantify the effects of key threats (fire, grazing and invasive species) to their populations, identify sites of high conservation value, and provide outcomes that support land management activities that are aligned with maintaining MNES habitat.

Project objectives include:

1. Quantify trends in the relative abundance of Yakka Skinks and Squatter Pigeons across the Galilee Basin.
2. Determine habitat characteristics influencing patch use at key sites.
3. Quantify the effects of grazing, fire and invasive species on populations of Yakka Skinks and Squatter Pigeons.

## The Galilee Basin

The Galilee basin is a large geological basin located in inland Queensland that covers an area of approximately 249,000 km<sup>2</sup> (Figure 1) (Australian Government 2018). The land overlying the basin contains several ecological communities including the Mitchell Grass Downs, Desert Uplands, Mulga, Brigalow Belt, Channel Country, Gulf Plains and Einasleigh Uplands bioregions. The most common vegetation is tussock grasslands in the west and open Eucalypt woodlands in the east. The climate is generally hot and dry, with an annual rainfall of 300 to 700 mm which is received during summer. Subsequently, surface water is relatively scarce; however, the headwaters of several major river systems originate in this region, and there are wetlands, springs and lakes in some areas which are home to a diverse array of flora and fauna, many of which are listed as rare or threatened under state and national legislation.

Primary production is the largest economic activity in the area with more than 95% of land used for pastoral grazing of sheep and cattle. Groundwater is heavily relied upon to water stock and the increased availability of water has allowed for the expansion of pastoralism across the Basin.

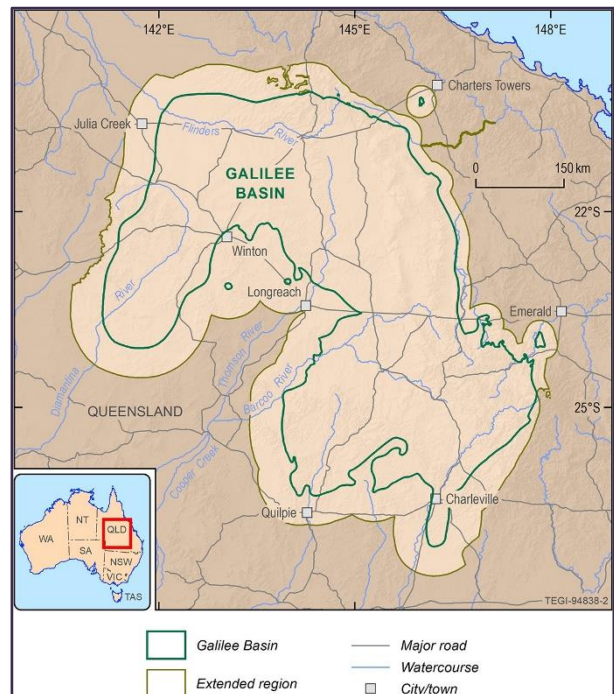


Figure 1 The Galilee basin The Galilee basin

# Monitoring and management of Yakka Skinks in the Galilee Basin

Stephen Peck, Jarrod Kath, Chloe Miller, Thuy Nguyen, Andrew Fichera, Vanessa Gorecki

## Introduction

The yakka skink (*Egernia rugosa*) is a large, robust skink that is endemic to Queensland (Ferguson & Mathieson 2014). The yakka skink is listed as vulnerable under Commonwealth legislation (*Environment Protection and Biodiversity Conservation Act 1999*) and vulnerable under QLD legislation (*Nature Conservation Act 1992*). Yakka skinks have a patchy distribution, with the majority of populations occurring in the Brigalow Belt and Mulga regions in southern and central Queensland though some isolated populations also occur as far south and west as St George and as far north as the Cape York Peninsula (ALA 2025).



Figure 2 An adult yakka skink (S. Peck).

Yakka skinks are found in a variety of habitat types from open forests to woodlands and low shrub lands. Main populations have been associated with Eucalypt

woodlands including poplar box (*Eucalyptus populnea*), ironbark (typically *E. melanophloia*) and Moreton bay ash (*Corymbia tessellaris*) as well as mulga (*Acacia aneura*) woodlands and white cypress pine (*Callitris glaucophylla*); usually in association with eucalypt species (Ferguson & Mathieson 2014). They can occur in disturbed or cleared areas, including grazing land, if suitable microhabitat features are present. Yakka skinks live in burrows and will often inhabit old rabbit burrows or modify tunnel erosion, sink holes and root cavities. They typically burrow where there is suitable substrate (firm but friable) and there is some form of structure such as large logs, log piles, stumps, partly buried rocks, stick rake piles, spoil heaps, sheds, houses and loading ramps (Ferguson & Mathieson 2014). These structures likely make burrowing easier and offer further protection. They are omnivorous and will consume soft plants and fruits and most invertebrates that venture into or near their burrow (Australian Gov 2008). They are a social species and often establish large family groups, with females bearing live young of around six per litter. Communal latrine sites are established near burrows (Australian Gov 2008).

Yakka skinks are under threat from loss of habitat, inappropriate roadside management, removal of microhabitat, ripping of rabbit warrens and predation by foxes and feral cats (Australian Gov 2008). Extensive clearing has been undertaken in the Brigalow Belt for agriculture and development since human settlement. Historically, this clearing was mostly limited to areas of fertile soils but has more recently shifted to the eucalypt woodlands on poorer soils, placing the yakka skink at further risk. Roadsides and reserves often provide important habitat in a cleared landscape and works that disturb these areas may impact yakka skink populations that are already isolated and at risk (Australian Gov 2008). Conservation advice for the yakka skink recommends more precise assessments of population size, distribution, ecological requirements and threatening processes as well as monitoring the effects of management actions (Australian Gov 2014).

The aim of this project was to quantify the effects of threats on the yakka skink by undertaking large and small-scale experimental trials investigating the effects of grazing, fire and invasive species on yakka skinks as well as conduct regional surveys and long-term monitoring. Specifically, the objectives were to:

1. Quantify trends in relative abundance of yakka skinks at multiple site;
2. Identify habitat characteristics influencing patch use at key sites; and
3. Identify the effects of fire, grazing and invasive species on populations of yakka skinks.

## Methods

### Yakka skink survey locations

We surveyed for yakka skinks at 55 locations within or near the Galilee Basin in central and southern Queensland (Figure 3).

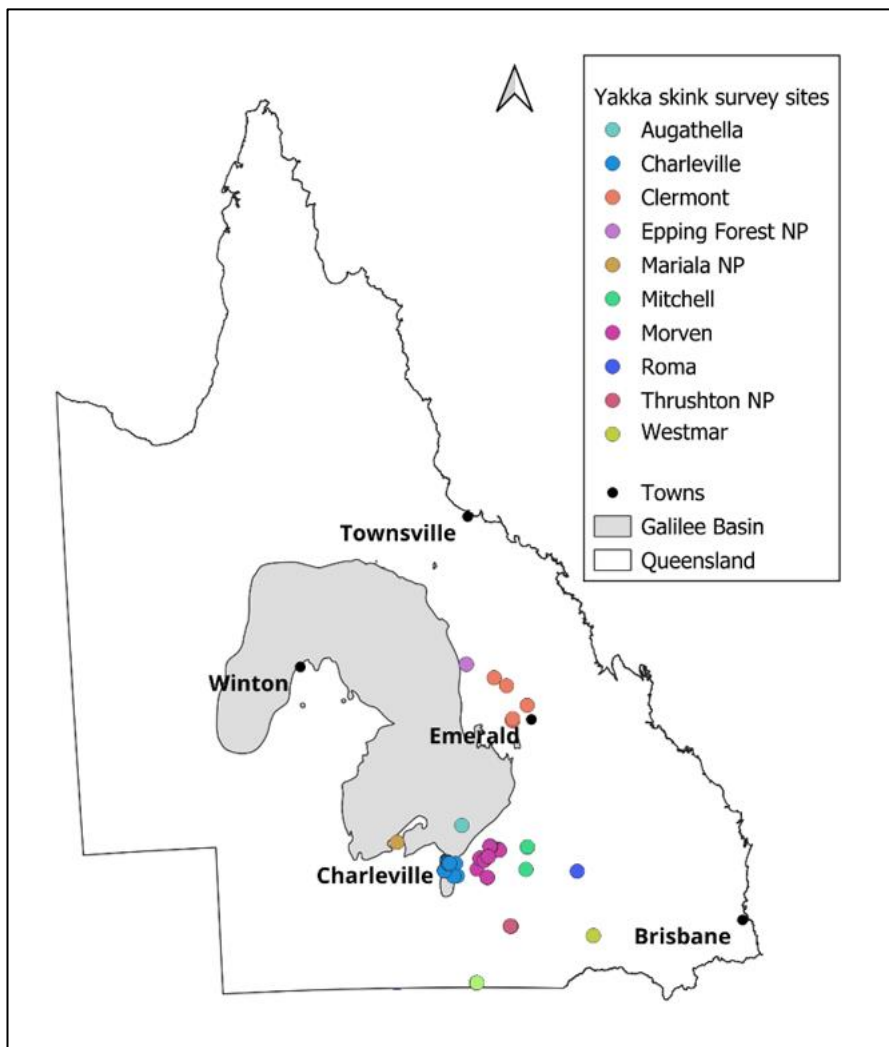


Figure 3 Yakka skink survey locations in relation to the Galilee Basin.

### Yakka skink surveys

Yakka skink presence/absence surveys were undertaken at 55 locations. In large remnant vegetation patches a 1 ha plot was searched. In linear vegetation strips such as road reserves and stock routes a 500 m linear search was undertaken. Yakka skink presence was confirmed if an active latrine site was detected. If no latrine was detected, then yakka skinks were considered absent.



Figure 4 A yakka skink latrine (left) and burrow (right) (S. Peck).

### Habitat characteristics – landscape level

We performed to explore drivers of yakka skink presence at a landscape scale using presence/absence data. Landscape variables were selected and extracted from multiple data sources, including satellite images and derived products available through Google Earth Engine Data Catalog, CSIRO and TERN Data Portal. A summary of these variables is provided in Table 1. The extracted data of all variables were integrated using the R platform to create a unified data frame containing all variables for each study site over the study period.

Table 1 Landscape variables extracted for landscape analysis for both yakka skinks and squatter pigeons.

Variable	Data source	Spatial resolution	Period	Description
<b>Climate</b> Tmean, Tmin, Tmax, Rainfall	<a href="#">GEE ERA5-Land</a>	11km	01/01/2022 - 31/12/2024	Climate variables, including daily mean temperature, daily minimum temperature, daily maximum temperature and daily rainfall, were extracted from ERA5-Land product using GEE platform. For each climate variable, a mean value over the study period was computed within 200m buffers surrounding each study site.
<b>Vegetation</b> NDVI, EVI	<a href="#">GEE MODIS MOD13Q1</a>	250m	01/01/2022 - 31/12/2024	Vegetation variables, including Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), were extracted from MODIS MOD13Q1 product using GEE platform. For each vegetation variable, a mean value over the study period was computed within 200m buffers surrounding each study site.
<b>Moisture Adjusted Vegetation Index (MAVI)</b>	<a href="#">GEE Sentinel 2</a>	10m	01/01/2022 - 31/12/2024	Moisture Adjusted Vegetation Index (MAVI) was computed using spectral bands from Sentinel-2 satellite images using GEE platform, applying to the following equation: $MAVI = (NIR - R) / (NIR + R + SWIR)$ (Zhu et al. 2014). A mean value of the index over the study period was

Variable	Data source	Spatial resolution	Period	Description
				computed within 200m buffers surrounding each study site.
<b>Fire scar</b> % covered by fire scar	<a href="#">TERN</a>	10m	01/01/2022 - 31/12/2024	Fire scar data was downloaded from the data portal of TERN Ecosystem Research Infrastructure. The percentage of fire scar was computed within 200m buffers surrounding each study site using zonal statistics tool in QGIS.
<b>Terrain Roughness Index (TRI)</b>	<a href="#">GEE SRTM</a>	30m	N/A	Terrain Roughness Index (TRI) was computed as a mean of absolute difference between elevation and local neighbourhood mean using a 3x3 window. The function was applied to SRTM 30m data using GEE platform. A mean value was computed within 200m buffers surrounding each study site.
<b>Tree canopy cover</b> % of tree cover	<a href="#">GEE Hansen</a> Global Forest Change 2000-2024	30m	2024	A variable of tree canopy cover in 2024, measured in percentage, was computed from Hansen dataset, including the tree cover for the year 2000 and the forest loss during 2000-2024. The analysis was carried out in GEE platform. A mean value of tree canopy cover was computed within 200m buffers surrounding each study site.
<b>Soil</b> clay %, sand % (0-5cm)	<a href="#">CSIRO Soil</a>	90m	N/A	Clay percentage and sand percentage in 0-5cm soil layer were downloaded from Soil and Landscape Grid National Soil Attribute Maps in CSIRO Data Portal. A mean value of clay and sand percentage were computed within 200m buffers surrounding each study site using zonal statistics tool in QGIS.

## Habitat characteristics – site level

A summary of yakka skink survey sites is shown in Table 2. Habitat characteristics were measured at positive sites (occupied by yakka skinks; n = 55), random sites (randomly selected sites 50 m from an occupied site; n = 55), random with log sites (an additional random site but selected due to a significant log feature; n = 21), cleared with significant regrowth sites (> 15 years old; n = 35) and cleared without significant regrowth sites (<15 years old; n = 30). The cleared sites were located adjacent to a positive site.

Habitat characteristics were recorded from a 10m x 10m quadrat (total area = 100m<sup>2</sup>). Habitat characteristics measured were those most likely to influence yakka skink occupancy. Habitat characteristics included live standing trees < 50 mm, 50 – 200 mm, and > 200 mm, dead standing trees < 50 mm, 50 – 200 mm, and > 200 mm, logs < 50 mm, log 50 – 200 mm, log > 200mm, canopy cover and vegetative ground cover data including percentages of bare earth, litter and vegetation.

Table 2 List of yakka skink survey sites.

Location	Date surveyed	Tenure type	Habitat type	Remnant/ non-remnant	Yakka skins present
Wallal	17/03/2025	Private Property	Cleared Mulga	Non-remnant	No
Wallal	17/03/2025	Private Property	Cleared Mulga	Non-remnant	No
Wallal	17/03/2025	Road Reserve	Mulga	Remnant	Yes
Wallal	17/03/2025	Road Reserve	Mulga	Remnant	Yes
Wallal	17/03/2025	Road Reserve	Mulga	Remnant	Yes
Morven West	16/03/2025	Road Reserve	Mulga/Box	Remnant	No
Ooline Park	14/10/2024	Road Reserve	Ooline/Mulga/Box	Remnant	No
Mariala National Park	13/10/2024	National Park	Mulga	Remnant	Yes
Charleville North	11/10/2024	Town Common	Mulga/Box	Remnant	Yes
Charleville	14/10/2024	Town Common	Mulga/Box	Remnant	Yes
Culgoa Flood Plain National Park – Toulby section	16/09/2024	National Park	Mulga	Remnant	Yes
Thrushton National Park	10/08/2024	National Park	Mulga/Box	Remnant	Yes
Thrushton National Park	10/08/2024	National Park	Mulga/Box	Remnant	Yes
Thrushton National Park	10/08/2024	National Park	Mulga/Box	Remnant	No
Thrushton National Park	10/08/2024	National Park	Mulga/Box	Remnant	Yes
Westmar	4/08/2024	Private Property	Box	Non-remnant	no
Morven West	2/04/2023	Road Reserve	Mulga	Remnant	No
Morven West	2/04/2023	Road Reserve	Mulga	Remnant	No
Morven North	3/03/2023	Stock Route	Mulga/Ironbark	Remnant	Yes
Morven North - Victoria downs	3/03/2023	Private Property	Cleared Mulga	Non-remnant	No

Location	Date surveyed	Tenure type	Habitat type	Remnant/ non-remnant	Yakka skins present
Morven North	3/03/2023	Stock Route	Mulga	Remnant	Yes
Morven North - Brenda	3/03/2023	Private Property	Cleared Mulga	Non-remnant	No
Morven South	3/03/2023	Private Property	Cleared Mulga	Non-remnant	No
Morven South	3/03/2023	Road Reserve	Mulga	Remnant	No
Morven South	3/03/2023	Road Reserve	Mulga	Remnant	Yes
Morven Conservation Park	2/03/2023	Conservation Park	Mulga/Box	Remnant	Yes
Morven- Winneba Rd	2/03/2023	Road reserve	Mulga/Box	Remnant	No
Claravale	8/02/2023	Private Property		Non-remnant	No
Claravale	8/02/2023	Private Property	Box	Remnant	No
Claravale	5/02/2023	Private Property	Cypress Pine	Remnant	No
Claravale	7/02/2023	Private Property	Box	Remnant	No
Claravale	8/02/2023	Private Property	Pulled Box	Non-remnant	No
Roma East	27/02/2023	Private Property	Box/sandlewood	Remnant	No
Riversleigh	24/11/2022	Road Reserve	Mulga/Box	Remnant	Yes
Charleville East (30km)	26/09/2022	Road Reserve	Mulga/Box	Remnant	No
Charleville East (50km)	26/09/2022	Road Reserve	Mulga/Box	Remnant	No
Morven West	14/07/2022	Road Reserve	Mulga/Box	Remnant	No
Dunheven	7/05/2021	Private Property	Box	Remnant	Yes
Glenmorgan	18/06/2021	Road Reserve	Brigalow	Remnant	No
Clermont	24/07/2021	Road Reserve	Cleared Brigalow	Remnant	No

Location	Date surveyed	Tenure type	Habitat type	Remnant/ non-remnant	Yakka skins present
South Capella	24/07/2021	Road Reserve	Brigalow/Box	Remnant	No
Belmah RR	24-25/07/2021	Resource reserve	Brigalow/Box	Remnant	No
Minerva Hills NP	25/07/2021	National Park	woodlands	Remnant	No
Orkadilla State Forest	31-1/09/2021	State Forest	Mulga/Box, Brigalow/Box	Remnant	Yes
Chesterton Range NP	2-3/09/2021	National Park	Brigalow/box	Remnant	Yes
Charleville	2021	Road Reserve	Mulga/Box	Remnant	Yes
Clermont Raglan Rd	1/11/2021	Road Reserve	Box/Brigalow	Remnant	No
Clermont, Raglan Rd	1/11/2021	Road Reserve	Box/Brigalow	Remnant	No
Clermont, Raglan Rd	1/11/2021	Road Reserve	Box/Brigalow	Remnant	No
Clermont, Raglan Rd	1/11/2021	Road Reserve	Ironbark/brigalow	Remnant	No
Epping Forest NP	2-5/11/2021	National Park	Corymbia woodlands	Remnant	Yes
Bathampton SF	6/11/2021	State Forest	Ironbark woodland	Remnant	No
Anakie, Rubyvale Rd	6/11/2021	Road Reserve	Box/Belah	Remnant	No
Sapphire Wetland Res	6/11/2021	Council Reserve	Box Woodland	Remnant	No
Cappella, Rubyvale Rd	7/11/2021	Road Reserve	Scrubby regrowth	Remnant	No

## Threatening processes assessment

### Grazing

Grazing impacts were measured as part of the habitat assessments. Ground cover and ground disturbance was recorded and scored on a scale of 1 – 5 with 1 being no disturbance and 5 complete removal of ground cover and extensive signs of pugging. Camera traps were also used to record livestock activity.

### Invasive species

Three discrete populations south of Charleville were identified as appropriate sites to undertake the invasive species impact study. The criteria for site selection were that each site should have multiple breeding aggregations, the sites were not likely to be impacted by any other disturbance, and there was guaranteed access to the sites over the length of the study. Most of the sites had previously been studied, so the long-term stability of the sites was known.

Six camera traps were deployed on a 500 x 250 m grid spaced 250 m apart. The aim was to detect feral cat and fox activity at each site but not necessarily associated with a known yakka skink aggregation. Cameras were mounted 300 mm above the ground, facing north/south. Spotlight searches, track monitoring (along dirt roads) and scat searches were also undertaken.

In October 2022 the camera traps were relocated to the breeding aggregations. One camera was set on each of the aggregations, focusing on the central point of the aggregation. Cameras were set to take three still images and one 30 second video. The cameras were checked October (pre-breeding) and March (post breeding). No attempt was made to identify individual cats and foxes.

Two aggregations from each of the sites were randomly selected to be fenced. A 25 m x 25 m x 1.8 m high mesh fence was constructed around each of the selected aggregations. The aggregation was positioned in the centre of the fenced area. The mesh aperture excluded invasive species from accessing the site but allowed yakka skinks and other small animals to move through.

All sites were trapped using baited Elliot traps for four consecutive nights between September/October (pre-breeding) and March/April (post-breeding). Morphological data including snout-vent length, tail length including regenerated tail length, head width, head length, and weight was collected from each lizard. Chin pattern photographs were used to identify individual lizards. A 5 mm tissue samples was collected from each lizard on the initial capture.

*Table 3 Yakka skink populations chosen for the invasive species impact study.*

Population	N. of breeding aggregations	Fenced aggregations
Charleville 1	6	2 and 5
Charleville 2	7	18 and 20
Charleville 3	6	24 and 25

## Modelling yakka skink response to a range of environmental variables

Structural equation model (SEM) was used to identify landscape scale drivers of yakka skink distribution. Structural equation models capture a wide range of different statistical models including path analytic models, factor analytic models and latent variable analysis. They provide a way to model the relationships between predictors and outcome variables simultaneously while capturing the ecological processes through hypothesised mediated pathways, referred to as path diagrams. Two structural equation models operating at different scales were developed to detect yakka skink response to a range of environmental variables. The first was at a landscape scale  $\sim >1\text{km}^2$  and utilised broader scale data and the second was at a site scale  $\sim 100\text{m}^2$  and utilised site level habitat assessment data.

### Data Preparation

Prior to fitting the models, each of the continuous predictor variables were standardised to have a mean of 0 and a standard deviation of 1 (Gelman & Hill, 2006). Binary variables were coded as 0 and 1. The standardisation of model predictors improves stability, computation time, and allows for the direct comparison of the relative magnitude of model parameter estimates.

### Model Fitting

Models were fit using the lavaan package (Rosseel, 2012) in the R statistical software (R Core Team, 2023). A series of structural equations were formulated to emulate the processes founded in the ecological literature. An assumption when fitting structural equation models with observed variables is that continuous variables generally follow a unimodal and symmetric distribution (generally normally distributed). Several of the observed predictor variables deviated from a generally normal distribution. To appropriately fit the models, the model estimator was changed to a maximum likelihood mean-adjusted (MLM) estimator, which has been shown to be robust to departures from this assumption by adjusting standard errors and using a Satorra-Bentler scaled test statistic (Curran, West, & Finch, 1996). The model results were interrogated by assessing missing paths using modification indices. A number of missing paths were shown to improve model fit and were reviewed against the ecological literature. These paths were included where justified.

### Model Parameter Estimates

Model parameter estimates and their 95% confidence intervals were extracted using the lavaan package (Rosseel, 2012). Standardised parameter estimate plots were generated using the ggplot package (Wickham, 2016). Path diagrams were developed to show the paths between predictor and outcome variables, where green paths indicate positive direct effects and red paths indicate negative direct effects. The thickness of the path arrows indicates the magnitude of the direct effect.

### Model Evaluation

As the model response variables were binary responses (presence or absence/active or inactive), receiver operator characteristic (ROC) plots and area under curve (AUC) values were utilised to appropriately measure the predictive performance of the fitted models. ROC curves are a plot of a model's specificity against its sensitivity. AUC values are the area under the ROC curve. It is the quantitative measure of how capable a model is at predicting model responses. AUC values near 1 represent a model with a strong ability to correctly predict a binary outcome, while values near 0.5 represent a model with no capacity. AUC values near 0 indicates a poor ability to predict a binary

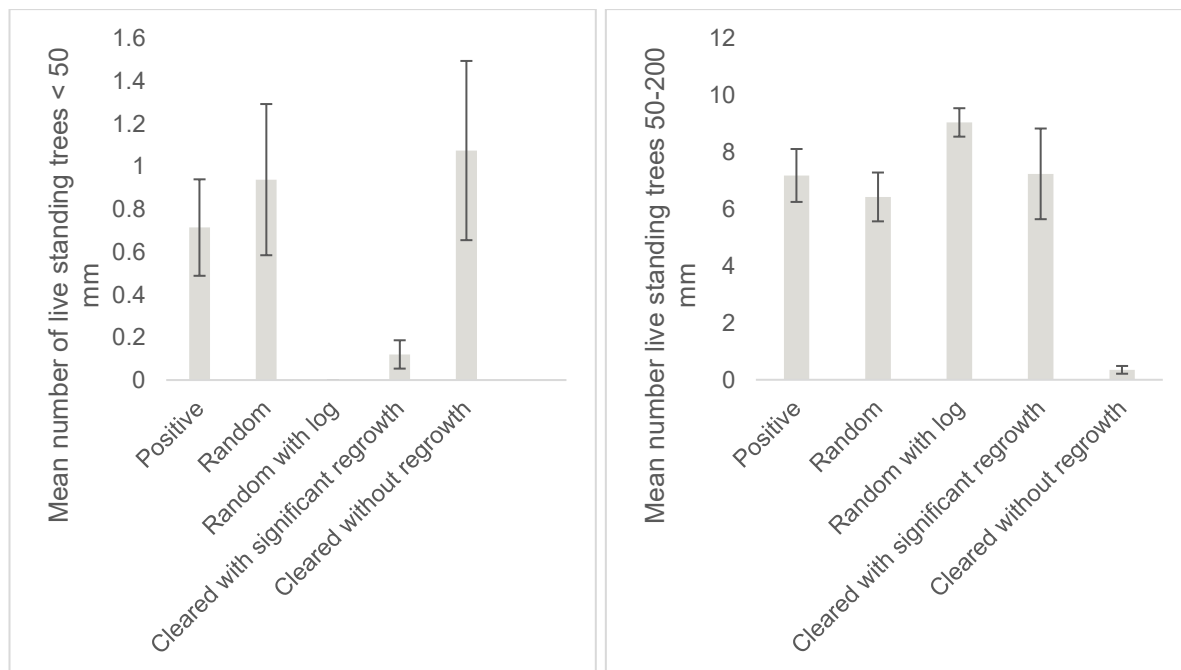
outcome, predicting values more incorrectly than if responses were chosen at random (Hajian-Tilaki, 2013). All AUC values were calculated using the pROC package (Robin, et al., 2011).

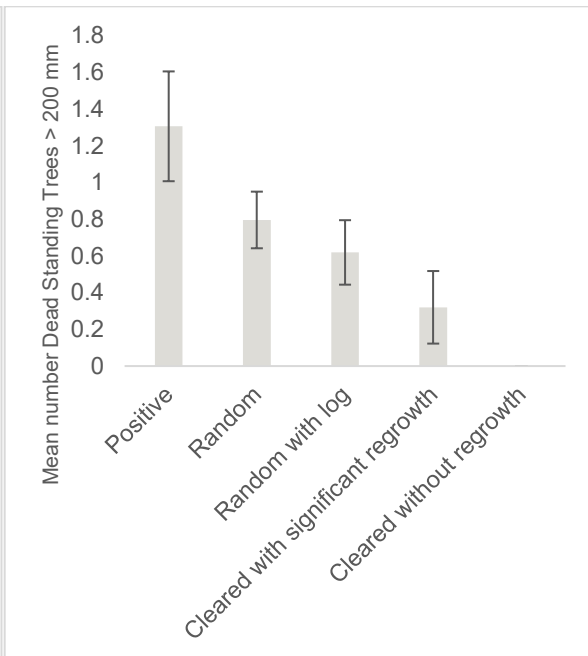
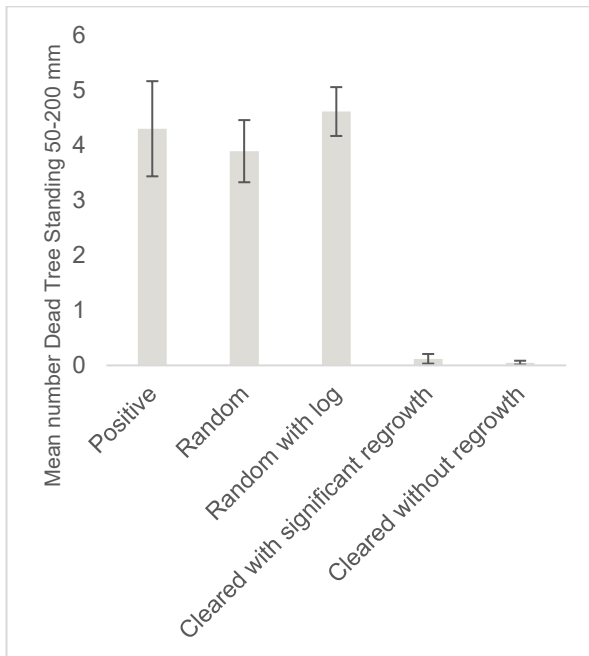
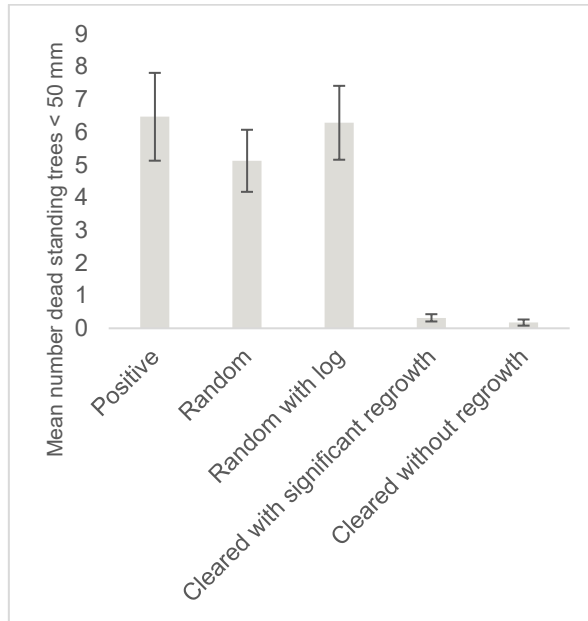
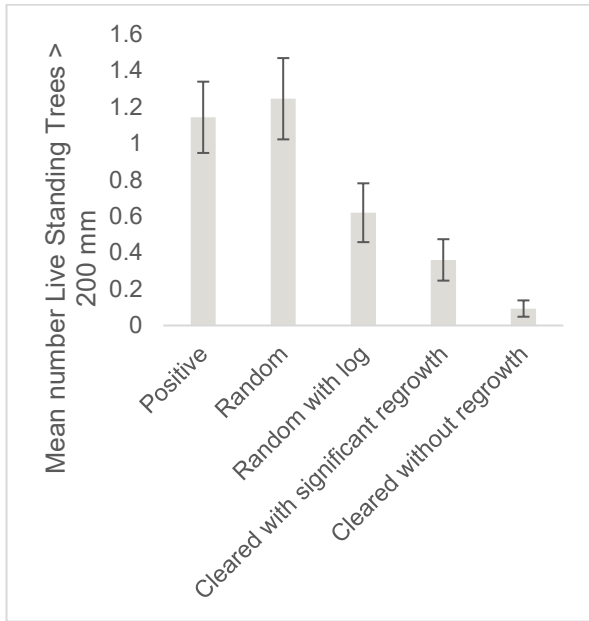
## Results

### Habitat characteristics

Significant differences were observed when comparing positive (occupied) sites to cleared with significant regrowth and cleared without significant regrowth sites (Figure 5). Neither of the cleared habitats contained habitat characteristics likely to support yakka skink populations or likely to encourage or support dispersal of yakka skinks into these habitats from adjacent remnant vegetation.

Positive, random and random with log sites were not significantly different for most characteristics (Figure 5). The number of logs > 200 mm at positive sites was significantly different when compared to the random sites but not when compared with random with log sites. The presence of large logs is likely to be an important characteristic for yakka skink establishment and ongoing occupation in remnant habitat.





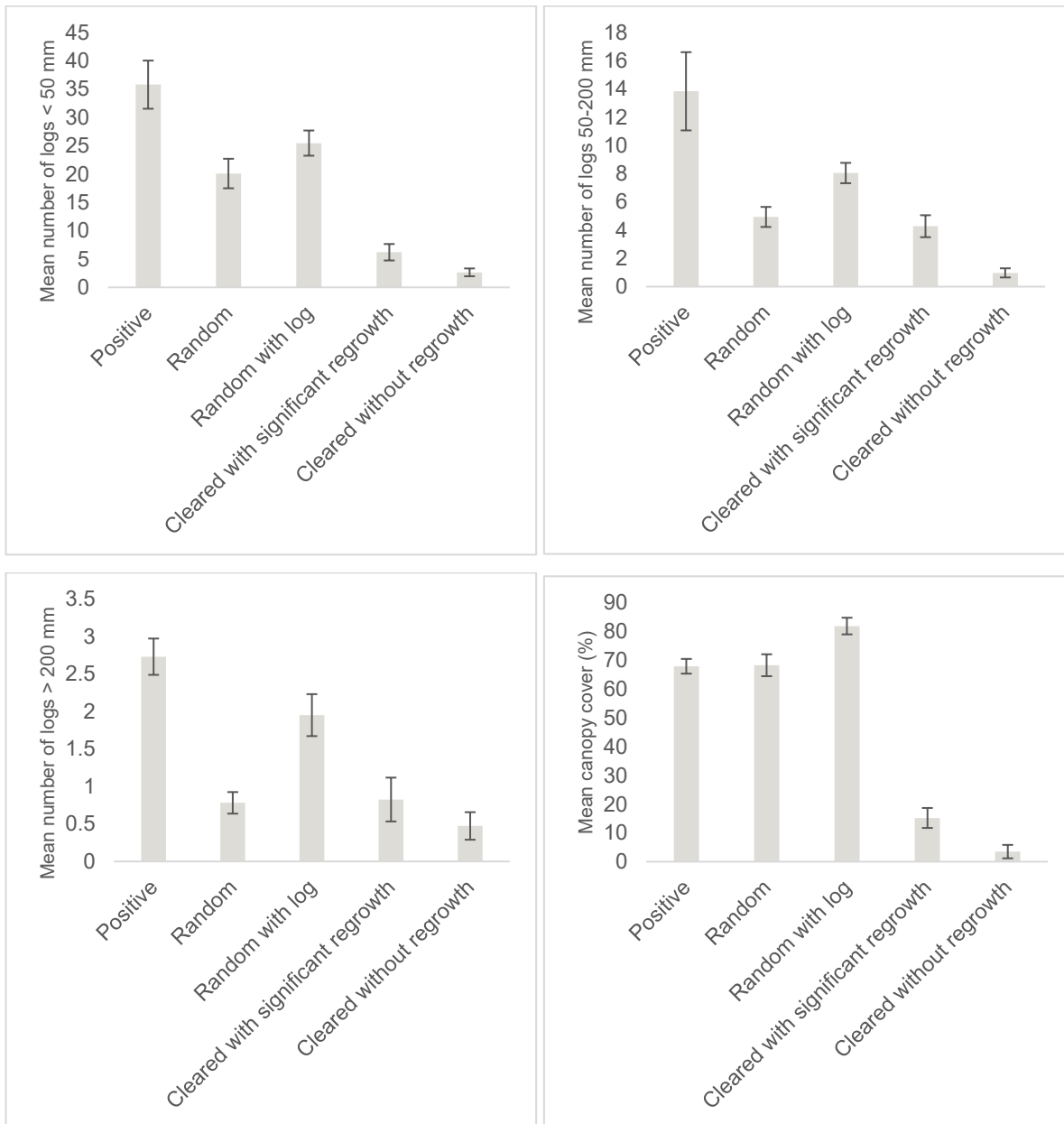


Figure 5 Habitat characteristics at positive (occupied), random, random with log, cleared with significant regrowth (> 15 years old) and cleared without significant regrowth (<15 years old) sites.

## Threatening processes

### Grazing

Initial assessments of grazing impacts on occupied sites indicated that grazing had little impact on yakka skink populations and habitat. Occupied sites in remnant vegetation were observed in areas with low levels of ground cover, which are unlikely to encourage significant enough grazing to cause habitat degradation. Cattle may cause minor burrow damage but given the location of burrows and woody debris this effect is considered minor. Grazing is not considered a major threat to the yakka skink and yakka skink habitat.

## Effects of invasive mammalian predators

No feral cats or foxes were detected during spotlight surveys. Feral cat and fox tracks and scats were detected at each of the three Charleville sites. Feral cats were detected on all cameras while foxes were only detected on 50% of the cameras.

Feral cats and foxes were detected at all the aggregations and activity was recorded in all months of the year. Feral cats and foxes were recorded demonstrating active hunting behaviours at the aggregations and inspected multiple burrows while visiting each aggregation. Feral cat and fox activity was recorded over lapping periods of yakka skink activity. No actual predation events were observed.

The number of individuals and total captures was greater at four fenced aggregations (2, 5, 24, 25) when compared to the mean values for the unfenced aggregations. Aggregations 18 and 20 were equal or lower than the mean unfenced values. Fencing to exclude feral cats and foxes had a positive effect on skink numbers.

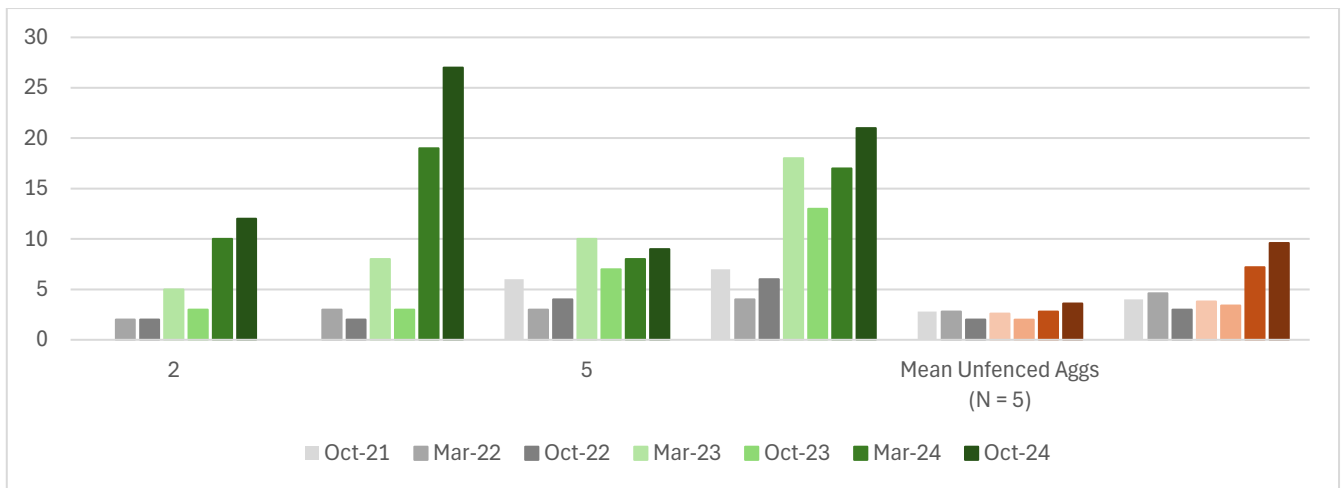


Figure 6 Charleville Site 1 Trap data. Aggregations 2, 5 (fenced), individuals and total capture data and mean unfenced aggregation data. Grey bars show pre-fence trap results, green bars and brown bars are post fence result.

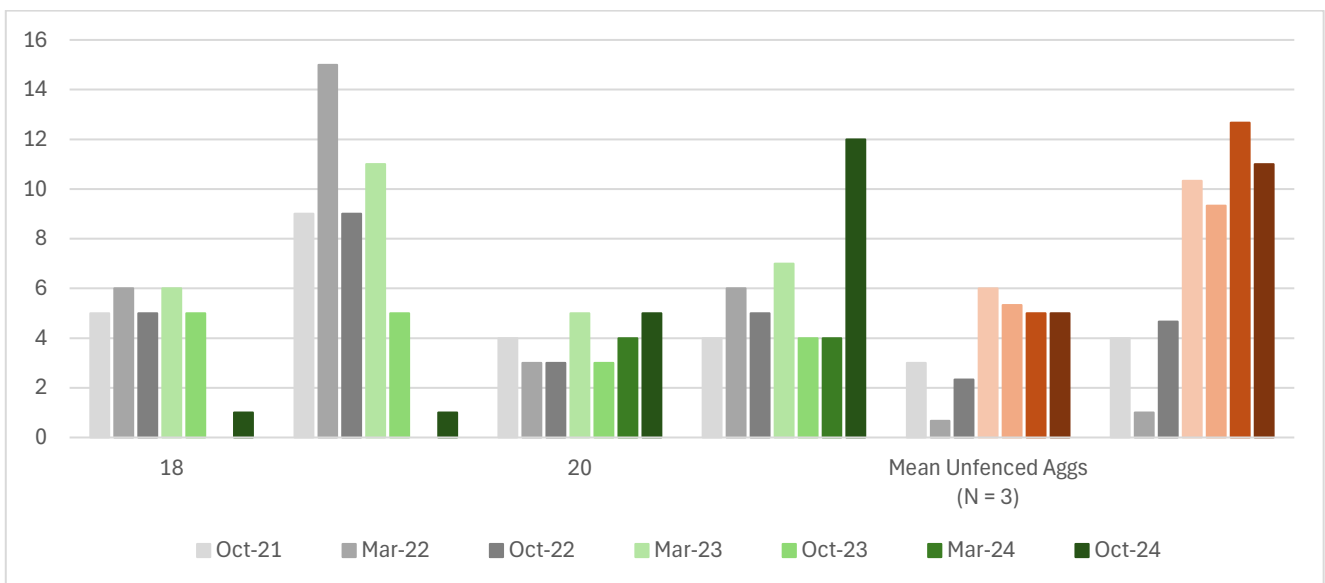


Figure 7 Charleville Site 2 Trap data. Aggregations 18, 20 (fenced), individuals and total capture data and total capture data and mean unfenced aggregation data. Grey bars show pre-fence trap results, green bars and brown bars are post fence result.

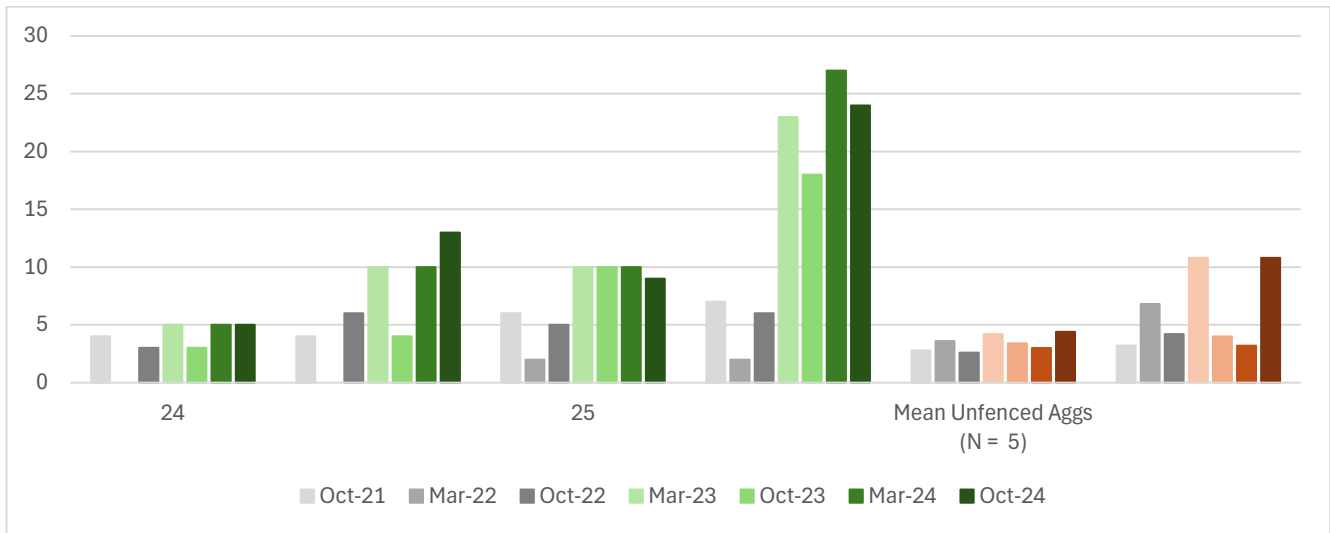


Figure 8 Charleville Site 3 Trap data. Aggregations 24, 25 (fenced), individuals and total capture data and mean unfenced aggregation data. Grey bars show pre-fence trap results, green bars and brown bars are post fence result.

### Structural equation model- landscape level

Figure 9 shows the standardised path coefficients, ordered from strongest positive effect to strongest negative effect. The blue points and intervals are positive and red are negative. The intervals shown are the 95% confidence intervals about the estimate. The path diagram in Figure 13 shows the directed paths and their associated path coefficients. The blue boxes are the exogeneous variables, and the orange boxes are the endogeneous variables. Red paths indicate a negative direct effect, green indicates a positive direct effect. The strongest direct effects on yakka skinks at the landscape scale in this model are Mean MAVI (0.14) and Mean Temperature (0.10).

The standardised path coefficients from the landscape-level structural equation model for the yakka skink identifies environmental variables influencing habitat and ecological conditions. The strongest positive effect observed was from tree recovery in 2024 on *ts\_mavi* (0.60), suggesting that areas with better post-disturbance tree recovery support higher habitat suitability or occupancy for the yakka skink. Tree recovery itself was positively influenced by both soil characteristics (0.34) and rainfall (0.31), highlighting the importance of abiotic factors in post-disturbance vegetation regeneration. Rainfall also had a direct positive effect on *ts\_mavi* (0.29), reinforcing its role as a key determinant of habitat conditions. Other positive but smaller effects included the influence of *ts\_mavi* on *res\_lsc* (0.14), and moderate contributions from soil and mean temperature to various response variables.

In contrast, the most negative effect was from mean temperature on tree recovery (-0.54), indicating that higher temperatures may suppress vegetation regeneration following disturbance. Fire presence also had a strong negative impact on tree recovery (-0.49), while negatively affecting *ts\_mavi* directly (-0.23). Soil properties and fire were both associated with reductions in *ts\_mavi*, further emphasising the detrimental effects of disturbance and certain substrate types. Overall, the model reveals that tree recovery is a critical intermediary variable influenced by climate and soil, with cascading effects on skink-relevant habitat metrics. Fire and temperature emerge as consistent negative drivers at the landscape scale, while rainfall and suitable soils are important for favourable ecological conditions.

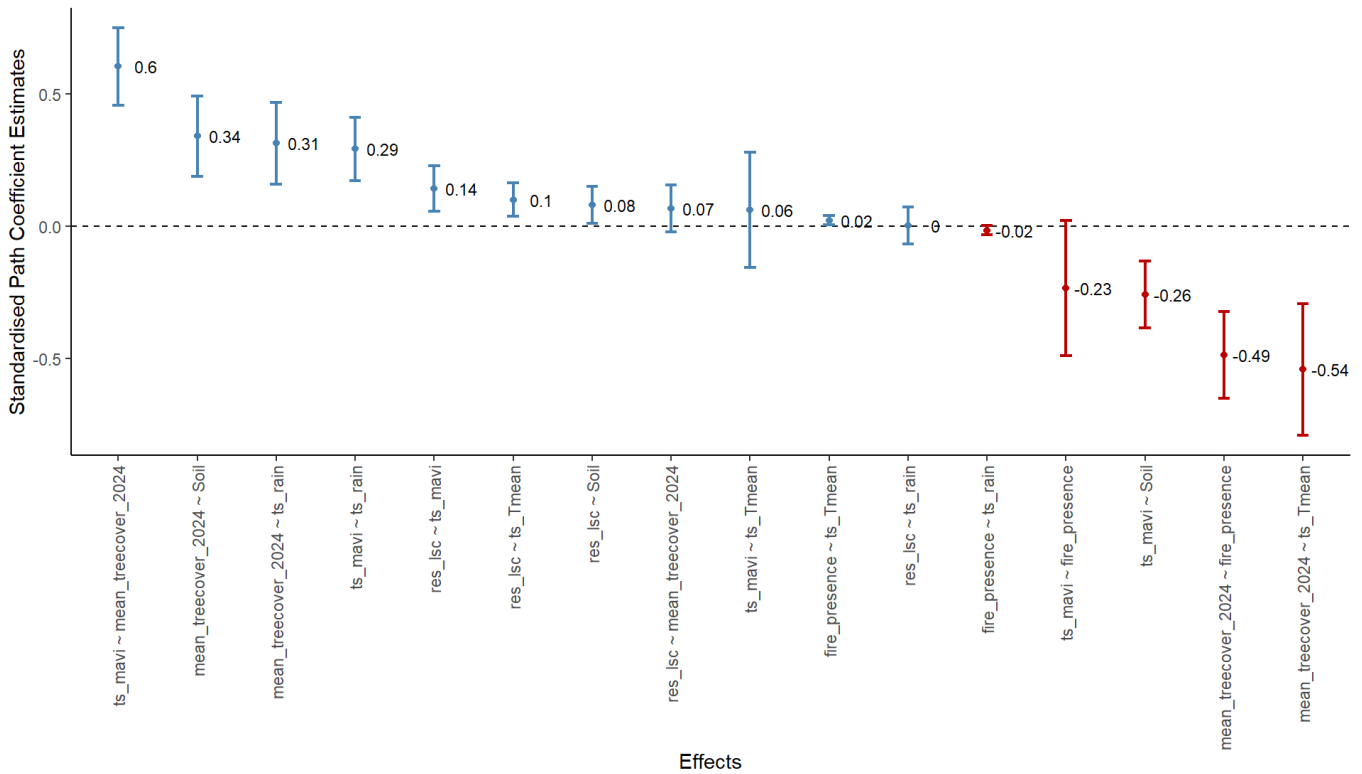


Figure 9 Standardised path coefficients of the landscape level yakka skink structural equation model, ordered from strongest positive effect to strongest negative effect. The intervals shown are the 95% confidence intervals about the estimate.

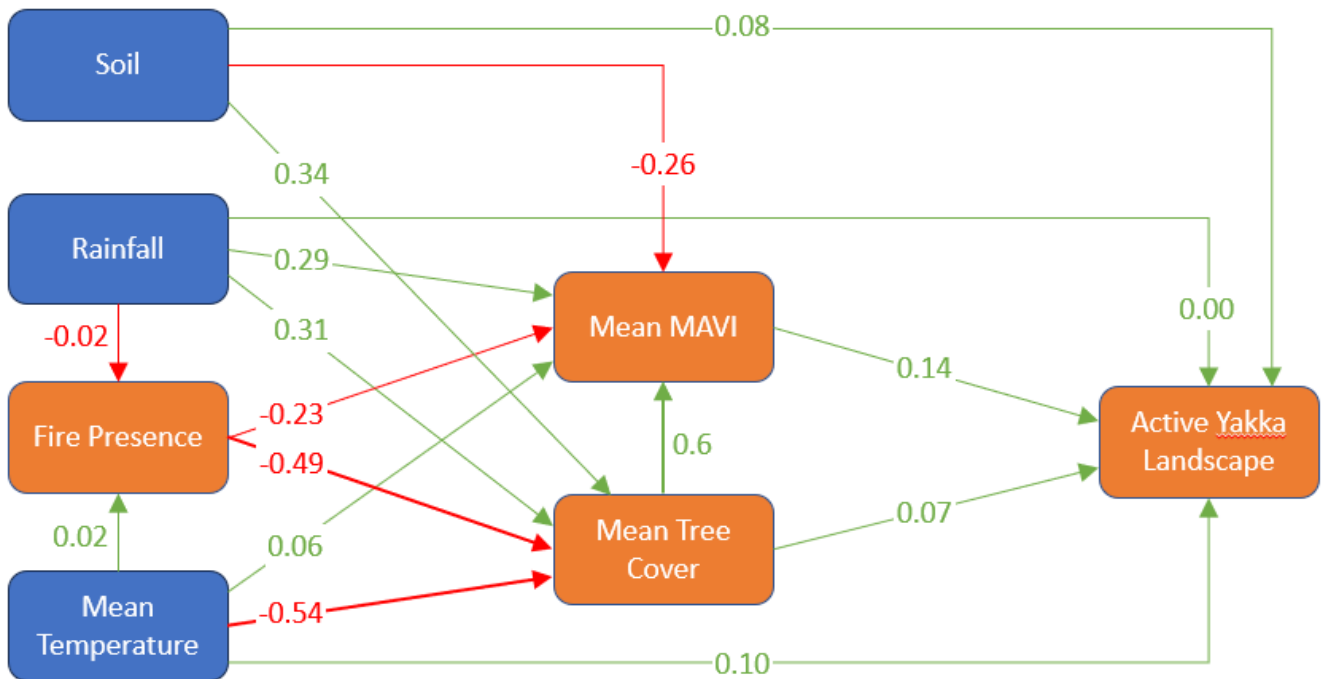


Figure 10 Path diagram of the landscape level yakka skink structural equation model showing the directed paths and their associated path coefficients. The blue boxes are the exogeneous variables, and the orange boxes are the endogenous variables. Red paths indicate a negative direct effect, green indicates a positive direct effect.

## Landscape level yakka skink model performance

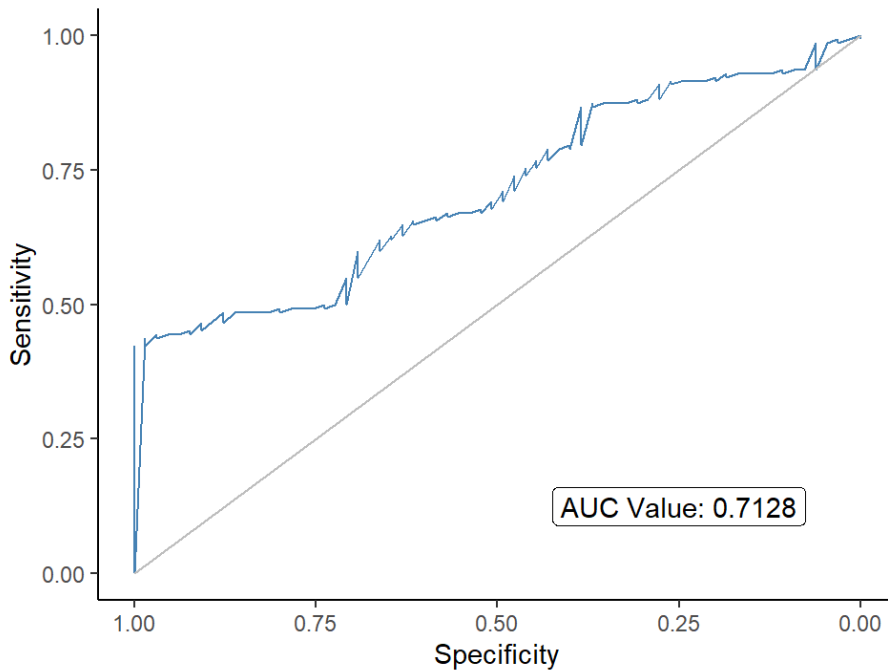


Figure 11 Receiver operating characteristic plot for the landscape level yakka skink structural equation model. AUC values near 1 represent a model with a strong ability to correctly distinguish pigeon presence, while values near 0.5 represent a model with no capacity. AUC values near 0 indicate a poor predictive ability to identify pigeon presence, where values are more incorrectly predicted than if they were chosen at random.

The ROC plot for the fitted landscape level yakka skink model indicates a moderate level of predictive performance, with a value of 0.7128. This suggests that the model has a reasonable ability to distinguish between presence and absence locations, performing substantially better than random (AUC = 0.5) but not approaching perfect discrimination (AUC = 1). The curve consistently lies above the diagonal reference line, reflecting a trade-off between sensitivity and specificity that favours effective classification across most threshold values. Overall, the model demonstrates acceptable fit and utility for predicting yakka skink habitat suitability at the landscape scale.

### Structural equation model- site level

Figure 12 shows the standardised path coefficients, ordered from strongest positive effect to strongest negative effect. The blue points and intervals are positive and red are negative. The intervals shown are the 95% confidence intervals about the estimate. Figure 13 is the path diagram showing the directed paths and their associated path coefficients. The blue boxes are the exogenous variables and the orange boxes are the endogenous variables. Red paths indicate a negative direct effect, green indicates a positive direct effect. The strongest direct effect on the yakka skink site level model was Log Count (0.20). The standardised path coefficients from the site-level structural equation model for the yakka skink show a gradient of effects among variables. The strongest positive effect is from live standing count to fire presence (0.39), followed by dead standing count to live standing count (0.38), and log count to dead standing count (0.32). Other moderate positive paths include dead standing count to ts\_mean (0.27), live standing count to ts\_mean (0.20), and res\_site to log count (0.19). Weaker positive effects are observed from dead standing count to ts\_rain (0.11), live standing count to ts\_rain (0.08), fire presence to ts\_mean (0.06), res\_site to fire presence (0.05), and dead standing count to ts\_mean (0.05).

On the negative side, the strongest effect is from dead standing count to fire presence (-0.90), indicating a strong inverse relationship. Smaller negative effects include res\_site to dead standing count (-0.07), fire presence to ts\_rain (-0.07), res\_site to live standing count (-0.08), and a negligible effect from dead standing count to ts\_mean (-0.01). These results suggest that vegetation structure, especially live and dead standing counts, plays a critical role in shaping fire presence and thermal microhabitat characteristics important for yakka skinks. There is also an interesting mediated pathway from *Live.Standing.Count* → *Dead.Standing.Count* → *Log Count* → *Active Yakka Site*.

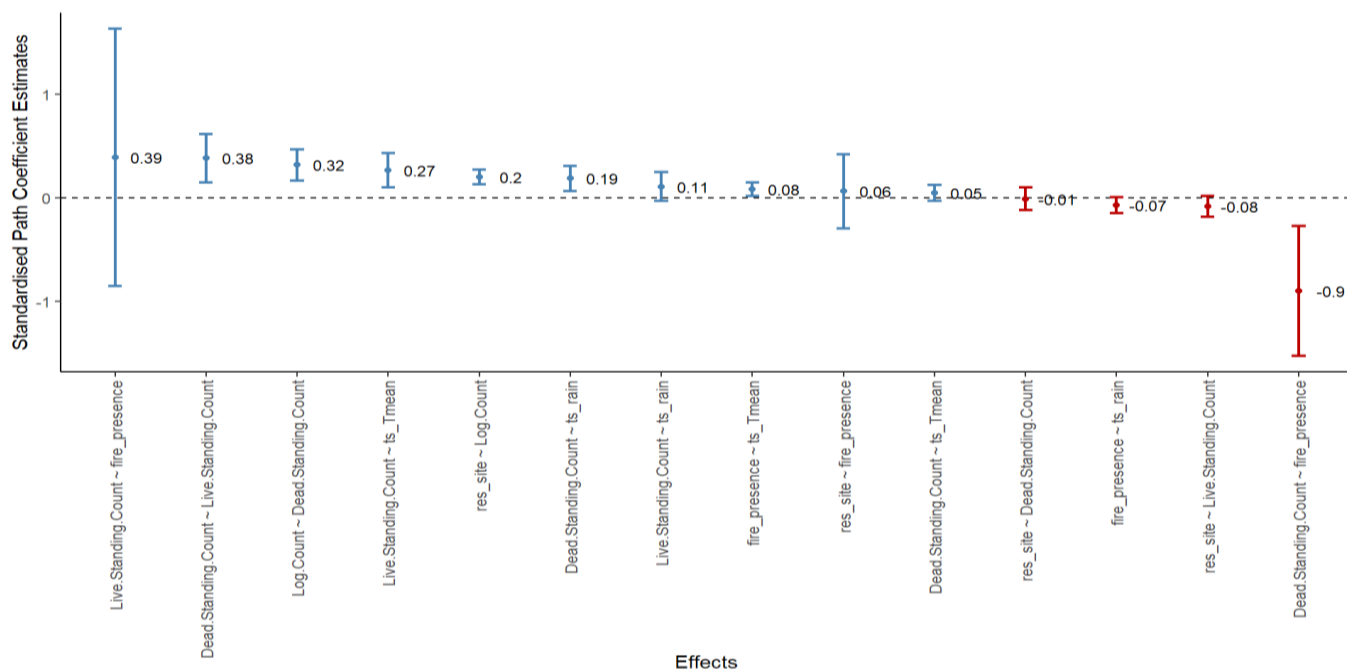


Figure 12 Standardised path coefficients of the site level yakka skink structural equation model, ordered from strongest positive effect to strongest negative effect. The intervals shown are the 95% confidence intervals about the estimate.

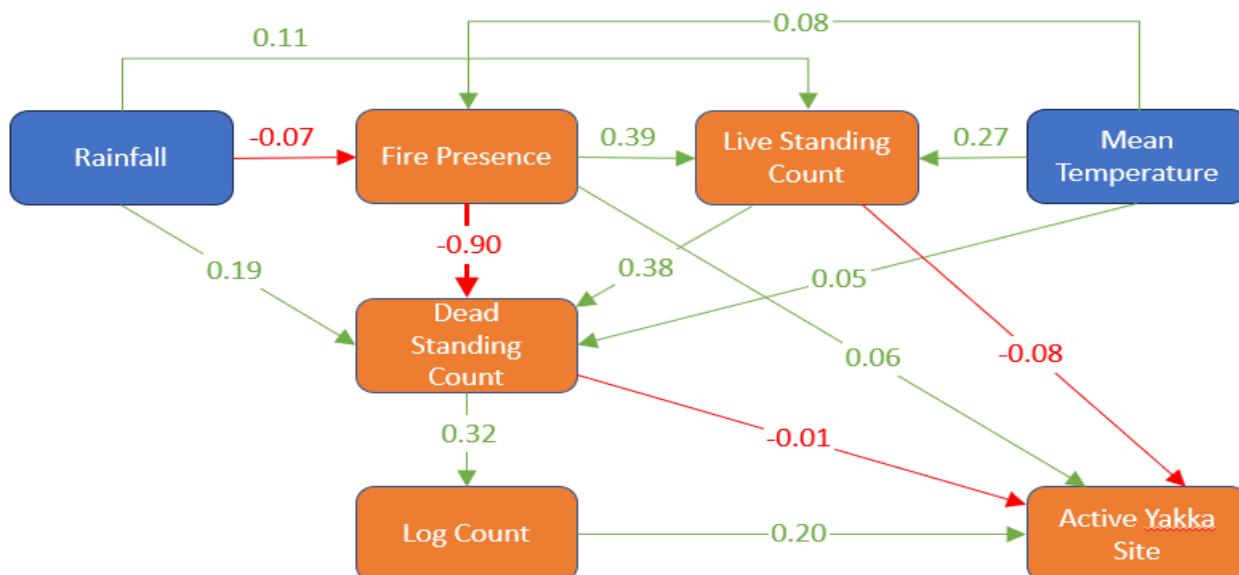


Figure 13 Path diagram of the site level yakka skink structural equation model showing the directed paths and their associated path coefficients. The blue boxes are the exogeneous variables, and the orange boxes are the endogenous variables. Red paths indicate a negative direct effect, green indicates a positive direct effect

## Site level yakka skink model performance

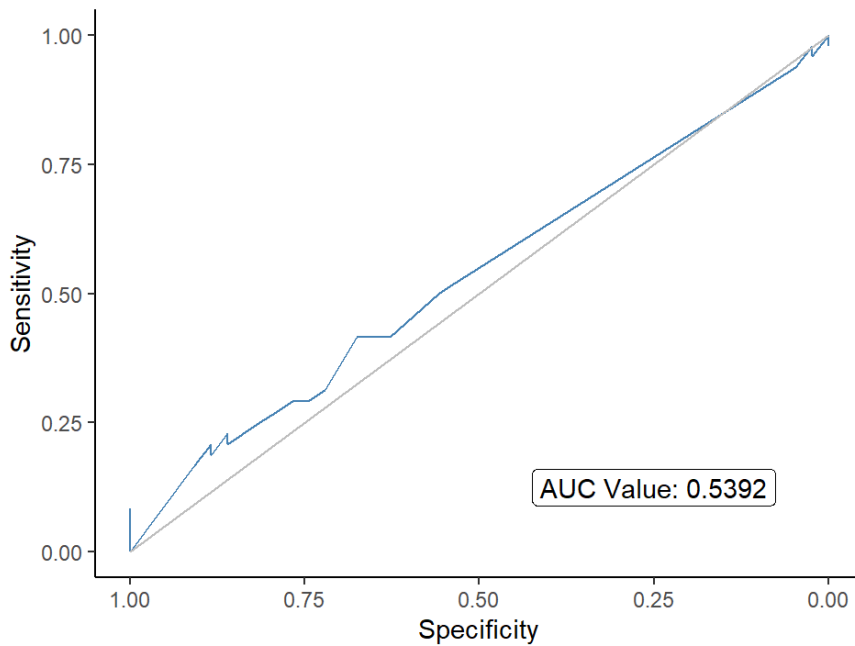


Figure 14 Receiver operating characteristic plot for the site level yakka skink structural equation model. AUC values near 1 represent a model with a strong ability to correctly distinguish pigeon presence, while values near 0.5 represent a model with no capacity. AUC values near 0 indicate a poor predictive ability to identify pigeon presence, where values are more incorrectly predicted than if they were chosen at random.

The ROC plot for the site-level yakka skink model indicates minimal predictive performance, with an AUC value of 0.5392. This is only marginally better than random chance (AUC = 0.5), suggesting that the model has limited ability to distinguish between sites where yakka skinks are present and absent. The curve stays close to the diagonal reference line across the range of specificity and sensitivity, indicating limited classification power. However, the model fit statistics were acceptable, so the model appears to be replicating what is observed in the data reasonably well. Overall, the model shows minimal discriminatory capacity at the site scale and may require refinement through the inclusion of more informative predictors. The poor predictive performance could also reflect the small sample size ( $n = 91$ ).

## Discussion

The results of this study have identified important insights into the habitat preferences and threats influencing yakka skink populations. Significant differences were observed between occupied (positive) sites and cleared areas, both with and without regrowth. Cleared habitats lacked key structural features required to support yakka skinks and did not appear suitable for either permanent occupancy or dispersal from nearby remnant vegetation. In contrast, positive sites were not significantly different from random or random-with-log sites for most habitat characteristics, though a notably higher number of large logs (>200 mm) was recorded at positive sites compared to random sites. This finding highlights the importance of large woody debris as a critical component for skink occupancy and persistence.

Initial assessments suggested that grazing had minimal impact on yakka skink populations. Occupied sites were often found in areas with low ground cover, where the likelihood of intensive grazing impacts was reduced. Although cattle may cause some incidental disturbance to burrows, these effects were

minor due to the protective nature of woody debris and burrow placement. As a result, grazing is not considered a significant threat to yakka skinks within remnant and regrowth habitats.

In contrast, invasive predators were frequently detected and pose a more substantial threat. Feral cats and foxes were observed at all study sites and across all seasons, with camera traps capturing footage of both species actively inspecting burrows. Though no direct predation events were recorded, this behaviour suggests a high risk for predator impact. Notably, higher capture rates and individual counts were recorded at four of six fenced aggregations compared to the mean values for unfenced sites. This indicates that predator exclusion through fencing has a positive influence on yakka skink abundance and activity.

Feral cats, in particular, are known to be efficient and opportunistic predators of small reptiles, especially in open or semi-open environments where vegetation cover is sparse. Yakka skinks, being largely ground-dwelling and reliant on surface refuges such as logs and burrows, are particularly vulnerable to predation if those refuges are compromised or insufficient. Foxes also pose a risk, with their broad diet and burrow-excavating behaviours further increasing the chances of skink encounters. The overlap in predator and skink activity patterns suggests that these interactions are not only possible but likely occurring.

The impact of predators is further underscored by the results from fenced aggregations, which were designed to exclude cats and foxes. Fenced sites supported a greater number of individuals and total captures compared to unfenced controls. This strongly implies that predator exclusion can provide measurable benefits to yakka skink populations, potentially by increasing survival and reducing stress or displacement. The lack of improvement at two fenced sites may relate to other limiting factors, such as habitat quality or time since fencing, but does not detract from the overall trend.

Given the widespread presence of feral predators and their known impacts on Australian reptiles more broadly, the risk to yakka skinks is both credible and concerning. Predator management, including targeted exclusion fencing or broad-scale control programs, should therefore be considered a critical component of yakka skink conservation. Without such measures, even high-quality habitat may fail to support stable populations due to persistent predation pressure.

At the landscape level, structural equation modelling showed that tree recovery (positively influenced by rainfall and soil) had the strongest positive effect on habitat suitability ( $ts\_mavi$ ), while mean temperature and fire had strong negative effects. The model had moderate predictive performance ( $AUC = 0.7128$ ). At the site level, vegetation structure was again key—live standing count had a strong positive influence on fire presence, and dead standing count strongly negatively influenced it. A pathway from live standing count through to skink activity via dead wood and logs was identified. Yakka skinks rely heavily on specific structural habitat features—particularly large logs—for shelter, thermoregulation, predator avoidance, and breeding. The modelling suggests that small-scale or low-intensity fires can act to create natural habitat such as logs, facilitating the development of these essential features through a multi-step ecological process.

Initially, small fires selectively damage standing vegetation and trees without clearing the entire site. This disturbance causes the death of some trees while allowing the broader habitat to persist, avoiding the complete structural loss seen in high-intensity or broadscale fires. Over time, the dead standing trees weaken, fall, and become part of the ground layer as coarse woody debris. These fallen logs are particularly important to yakka skinks, as they create stable microhabitats that offer protection from predators, moderate thermal extremes, and support invertebrate prey populations.

The pathway described in the model highlights a positive feedback loop where natural disturbance processes, like fire, gradually enhance habitat suitability for the skinks. The pathway highlights the ecological value of fire as a driver of heterogeneity and structural complexity in vegetation communities. This finding supports the view that appropriately managed fire regimes—particularly those that mimic natural, patchy, low-intensity burns—can contribute positively to long-term habitat quality. Importantly



though at the landscape scale, where possible larger fires take hold, the dynamics are different. Large scale fires may have a negative effect by reducing large areas of forest (as indicated by the Mean Tree cover variable) and reducing ground cover /productive vegetation (as indicated by the Mean MAVI variable)

Importantly, these modelling outputs identify the importance of fire management strategies for the conservation of the yakka skinks. Overly frequent or intense fires may destroy key habitat components before they can develop, while complete fire exclusion may limit the creation of new shelter sites and lead to long-term habitat senescence. Therefore, incorporating controlled, small-scale burns into conservation planning could help maintain a dynamic landscape where suitable shelter continues to be created over time. When combined with other measures such as predator control and protection of remnant vegetation, fine-scale fire management could play a critical role in enhancing habitat availability and connectivity for yakka skinks across their range.

## **Management recommendations**

### **Promote small-scale, controlled burns**

Small-scale, low-intensity burns are essential for maintaining habitat complexity without causing widespread damage. These controlled fires selectively impact older vegetation and promote the gradual formation of deadwood and logs. Such features are critical for yakka skinks, offering shelter, thermoregulation, and protection from predators. Careful monitoring of fire intensity ensures that ground cover remains intact, preserving microhabitats and minimizing erosion or habitat loss.

### **Avoid or mitigate large-scale fires**

Large, high-intensity fires can devastate skink habitats by removing vegetation cover and destroying structural features like logs and burrows. To prevent this, firebreaks and buffer zones should be strategically placed to contain wildfires. Early detection systems and rapid response teams are vital for suppressing fires before they escalate. Landscape-level planning should aim to maintain habitat heterogeneity and connectivity, ensuring that skinks can move between habitat patches and avoid isolated population declines.

### **Enhance log habitat availability**

Logs and coarse woody debris are vital for yakka skink survival, serving as refuges and breeding sites. In areas where natural log formation is limited—due to past clearing or firewood collection—artificial log placement could help restore habitat functionality. Conservation efforts should also focus on protecting existing deadwood from removal, recognizing its ecological value and role in supporting not only skinks but a broader community of native species.

### **Monitor vegetation indices and tree cover**

Tracking vegetation health and structure is key to understanding habitat suitability over time. Remote sensing tools can monitor indicators like Mean MAVI (vegetation productivity) and Mean Tree Cover, providing insights into how fire and climate affect skink habitats. Integrating these metrics into adaptive management frameworks allows for informed decisions about fire planning, restoration efforts, and long-term habitat viability.

## Future research priorities

### **Predator impact assessment**

Quantify the actual impact of feral cats and foxes on Yakka skink populations through direct observation, camera traps, and scat analysis to refine predator control strategies.

### **Fire regime effects on habitat quality**

Investigate how different fire frequencies and intensities influence the development of coarse woody debris and microhabitats essential for skink survival.

### **Restoration techniques and effectiveness**

Test various habitat restoration methods, such as artificial log placement and vegetation enrichment, to determine their success in supporting skink occupancy and reproduction.

### **Long-term monitoring frameworks**

Develop standardized, long-term monitoring protocols to track population trends, habitat changes, and the effectiveness of management interventions.

### **Climate change vulnerability**

Model how projected changes in temperature and rainfall will affect skink distribution, and habitat suitability, especially in marginal areas.

# Monitoring and management of Squatter Pigeons in the Galilee Basin

John van Osta, Jarrod Kath, Chloe Miller, Thuy Nguyen, Andrew Fichera, Gary Young, Vanessa Gorecki

## Introduction

The squatter pigeon (southern subspecies) (*Geophaps scripta scripta*) is listed as Vulnerable under Commonwealth legislation (*Environment Protection and Biodiversity Conservation Act 1999*), Vulnerable under QLD legislation (*Nature Conservation Act 1992*), and Critically Endangered under NSW legislation (*Biodiversity Conservation Act 2016*) (NSW Gov 2021).

It is a medium-sized, ground-dwelling, and ground-nesting pigeon that was once common and widespread nationally. It now occurs mostly in northern and central Queensland with sparse populations in southern Queensland and rare occurrences in northern New South Wales. Squatter pigeons are found in tropical and dry open



Figure 15 A flock of squatter pigeons (Wiley 2011).

sclerophyll woodlands and savannahs that have a grassy understorey and are close to permanent water sources. They feed on a variety of seeds from the ground as well as insects to a lesser degree. They nest amongst sheltered vegetation such as grass tussocks and bushes with clutches generally containing two eggs that are incubated for 15-17 days.

Squatter pigeons are primarily under threat from habitat loss due to clearing for agriculture, habitat degradation due to overgrazing and drought, trampling of nests by livestock, flooding of nests due to heavy rainfall, predation by foxes and feral cats, and illegal shooting.

The aim of this project was to conduct long-term surveying and monitoring of squatter pigeons and investigate the effects of grazing, fire and invasive species on populations of squatter pigeons. Specifically, our objectives are:

1. Quantify trends in relative abundance of squatter pigeons at each site;
2. Identify habitat landscape characteristics influencing squatter pigeon patch use at key sites; and
3. Identify the effects of grazing, fire and invasive species on populations of squatter pigeons.



*Figure 16 Squatter pigeon being a squatter pigeon. (Photo: J.Kath)*

## **Methods**

### Squatter pigeon monitoring locations

We surveyed and monitored squatter pigeons at three locations – Morven, Hughenden, and Torrens Creek – within or near the Galilee Basin in central Queensland (Figure 17). Fifteen monitoring sites were chosen at each location, for a total of 45 monitoring sites (Table 4).

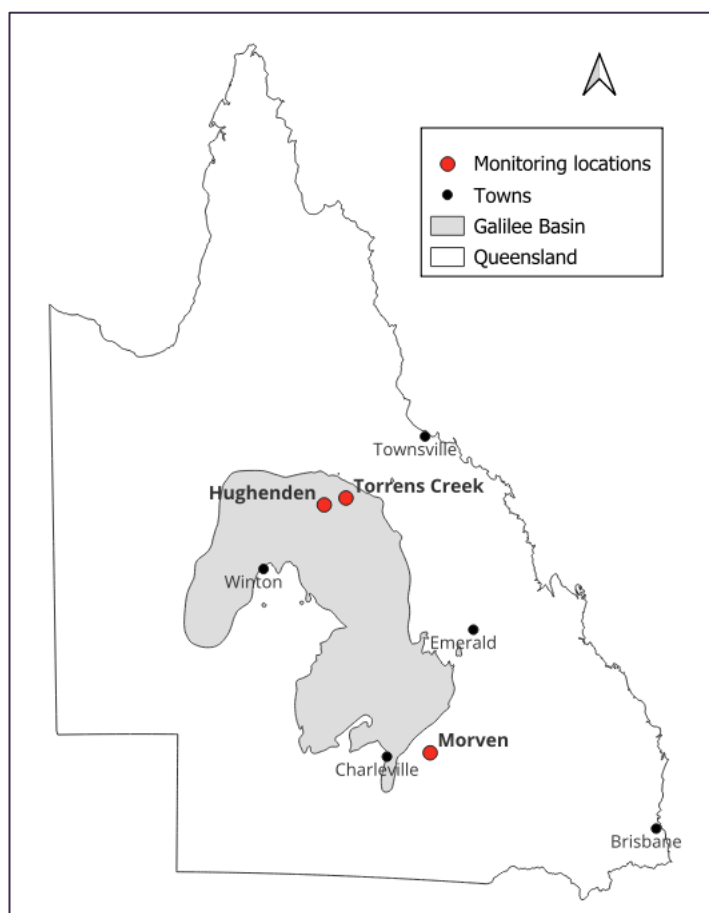


Figure 17 Squatter pigeon monitoring locations in relation to the Galilee Basin.

## Morven

Monitoring sites at Morven were situated in Chesterton Range National Park, Orkadilla State Forest and on the adjacent cattle station Mount Maria, approximately 35 km north-east of the township of Morven (Figure 18, Table 4). This allowed for a direct comparison between the uncleared and ungrazed park areas and the cleared and grazed agricultural land nearby. Morven receives an annual mean rainfall of 499 mm, and with mean temperatures ranging from 19.7°C in winter (July) and 35.3°C in summer (January) (Bureau of Meteorology 2025). Within the park, the most common habitat is dry eucalypt woodlands on depositional plains with some *Callitris spp.* at elevated locations (Queensland Government 2025). Mount Maria consists of mostly non-remnant grazing land containing mitchell grass (*Astrebla spp.*) and bluegrass (*Dicanthium spp.*) tussock grasslands. Patches of mulga shrublands, (*Acacia aneura*) and brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) woodlands are still present on Mount Maria. Waterpoints within the park are either old farm dams or semi-permanent creeks, while waterpoints on Mount Maria are larger dams and stock troughs.

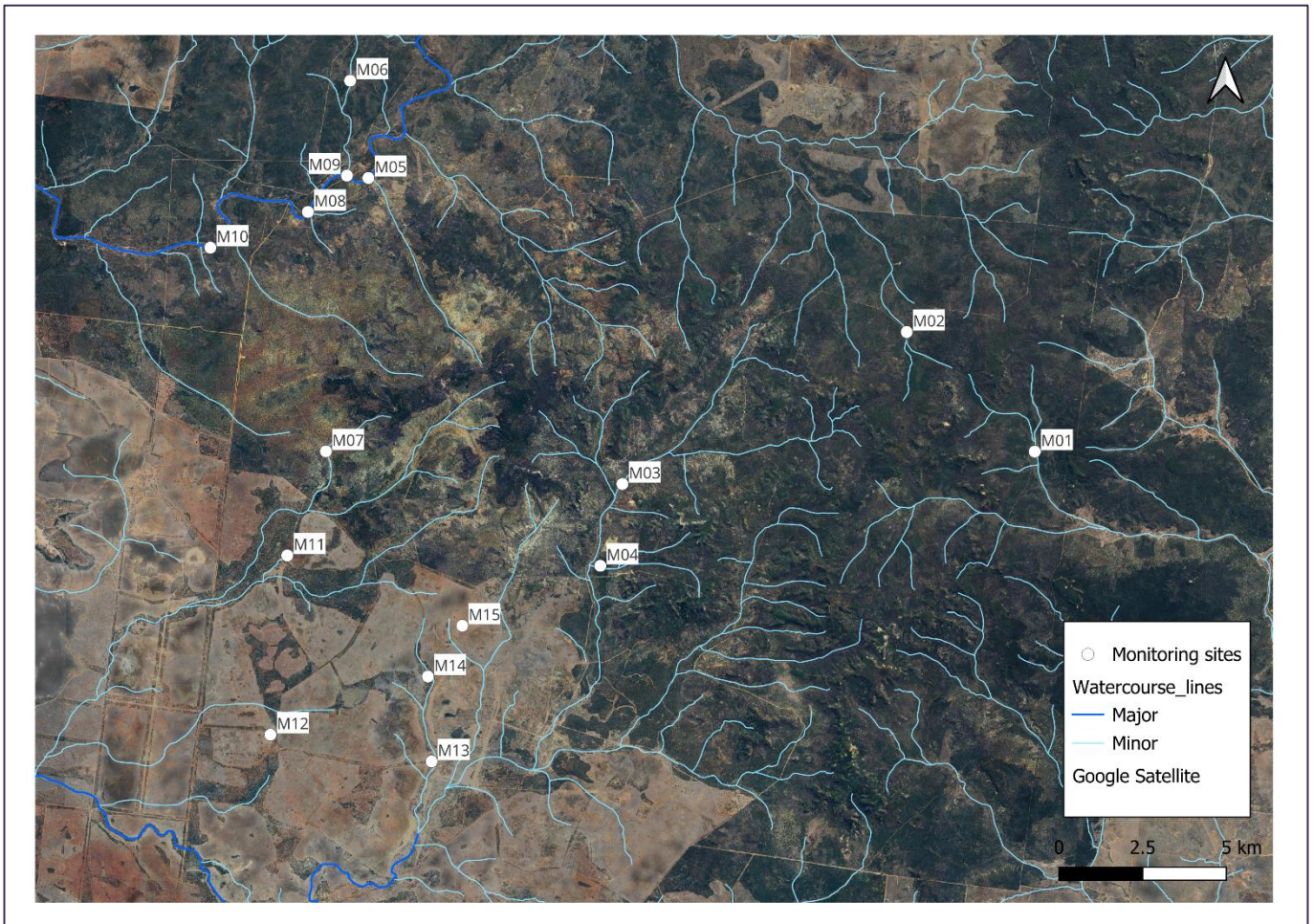


Figure 18 Squatter pigeon monitoring sites at Morven (Orkadilla State Forest, Chesterton Range National Park, and Mount Maria station).

### Hughenden and Torrens Creek

Monitoring sites at Hughenden were situated on Railview station, a 30,000 ha cattle grazing property 30 kms east of Hughenden township (Figure 19, Table 4). Hughenden receives an annual mean rainfall of 492.2 mm, and mean temperatures range from 25.0°C in winter to 35.8°C in summer (Bureau of Meteorology 2025). Habitat includes non-remnant grazing land, mitchell and bluegrass tussock grasslands on blacksoil downs, dry Eucalypt woodlands, and a variety of *Acacia spp.* woodlands (Queensland Government 2025). Waterpoints at Hughenden include seasonal channels, dams, turkeys nests and troughs.

Torrens Creek is located 85 kms east of Hughenden township and our monitoring sites were situated on Strathelen station, a 20,000 ha cattle grazing property (Figure 19, Table 4). Habitat consists of mostly dry Eucalypt woodlands on depositional or sandy plains with some non-remnant grazing land (Queensland Government 2025). Waterpoints at Torrens Creek include dams, turkeys nests, troughs, Torrens Creek itself, and a small number of wetlands.

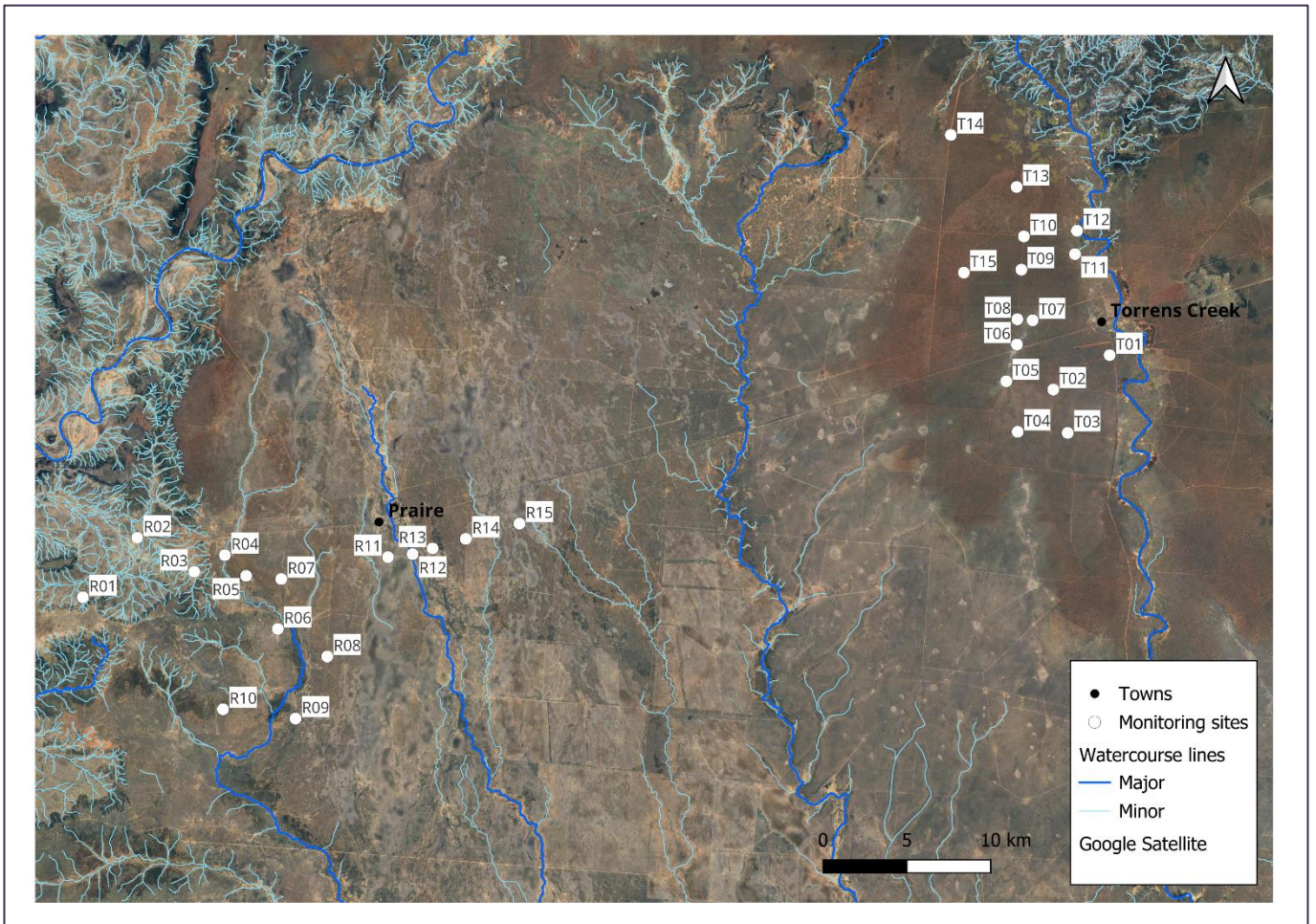


Figure 19 Squatter pigeon monitoring sites at Hughenden (Railview station) and Torrens Creek (Strathelen station).

Table 4 List of squatter pigeon monitoring sites.

Location	Property	Site	Latitude	Longitude	RE description	Water source
Morven	Chesterton NP	M01	-26.17664	147.44661	Eucalypt dry woodlands on inland depositional plains	Dam
Morven	Chesterton NP	M02	-26.14454	147.40823	Eucalypt dry woodlands on inland depositional plains	Dam
Morven	Chesterton NP	M03	-26.18569	147.32341	Eucalypt dry woodlands on inland depositional plains	Dam
Morven	Chesterton NP	M04	-26.20753	147.31346	Eucalypt dry woodlands on inland depositional plains	Dam
Morven	Chesterton NP	M05	-26.10343	147.24732	Eucalypt dry woodlands on inland depositional plains/Callitris woodland-open forest	Creek
Morven	Orkadilla SF	M06	-26.07728	147.2422	Eucalypt dry woodlands on inland depositional plains/Callitris woodland-open forest	Dam
Morven	Orkadilla SF	M07	-26.17741	147.23508	Callitris woodland-open forest/ Dry eucalypt woodlands to open woodlands, mostly on shallow soils in hilly terrain/ Heathlands and associated scrubs and shrublands on coastal dunefields and inland/ elevated locations	Dam
Morven	Orkadilla SF	M08	-26.1126	147.22927	Eucalypt dry woodlands on inland depositional plains/Callitris woodland-open forest	Creek
Morven	Orkadilla SF	M09	-26.10279	147.24092	Eucalypt dry woodlands on inland depositional plains/Callitris woodland-open forest	Creek
Morven	Orkadilla SF	M10	-26.12226	147.20015	Eucalypt dry woodlands on inland depositional plains/Callitris woodland-open forest	Creek
Morven	Mount Maria station	M11	-26.20514	147.2233	Non-remnant	Dam
Morven	Mount Maria station	M12	-26.25341	147.21834	Acacia aneura (mulga) dominated open-forests, woodlands and shrublands	Trough
Morven	Mount Maria station	M13	-26.26006	147.26751	Astrebla spp. (mitchell grass), Dichanthium spp. (bluegrass) tussock grasslands/ Acacia harpophylla (brigalow) sometimes with Casuarina cristata (belah) open forests to woodlands on heavy clay soils	Dam
Morven	Mount Maria station	M14	-26.23825	147.26693	Astrebla spp. (mitchell grass), Dichanthium spp. (bluegrass) tussock grasslands/ Acacia harpophylla (brigalow) sometimes with Casuarina cristata (belah) open forests to woodlands on heavy clay soils	Dam
Morven	Mount Maria station	M15	-26.22396	147.27564	Non-remnant	Trough
Hughenden	Railview station	R01	-20.91032	144.43294	Non-remnant	Dam

Location	Property	Site	Latitude	Longitude	RE description	Water source
Hughenden	Railview station	R02	-20.87785	144.46548	Astrebla spp. (mitchell grass), Dichanthium spp. (bluegrass) tussock grasslands/ Mixed species woodlands - open woodlands (Atalaya hemiglauca (whitewood), Lysiphyllum spp., Acacia tephрина (boree), wooded downs	Trough
Hughenden	Railview station	R03	-20.89669	144.49787	Eucalypt dry woodlands on inland depositional plains	Dam
Hughenden	Railview station	R04	-20.88796	144.51563	Eucalypt dry woodlands on inland depositional plains	Trough
Hughenden	Railview station	R05	-20.89934	144.52761	Eucalypt dry woodlands on inland depositional plains	Dam
Hughenden	Railview station	R06	-20.92814	144.5453	Eucalypt dry woodlands on inland depositional plains	Trough
Hughenden	Railview station	R07	-20.90135	144.54818	Eucalypt dry woodlands on inland depositional plains	Trough
Hughenden	Railview station	R08	-20.94344	144.57344	Eucalypt dry woodlands on inland depositional plains	Trough
Hughenden	Railview station	R09	-20.9766	144.55471	Non-remnant	Trough
Hughenden	Railview station	R10	-20.97098	144.51319	Eucalypt dry woodlands on inland depositional plains	Trough
Hughenden	Railview station	R11	-20.89041	144.60914	Astrebla spp. (mitchell grass), Dichanthium spp. (bluegrass) tussock grasslands	Trough
Hughenden	Railview station	R12	-20.88898	144.62333	Eucalypt dry woodlands on inland depositional plains/Eucalypt open forests to woodlands on floodplains	Trough
Hughenden	Railview station	R13	-20.88606	144.63479	Acacia cambagei (gidgee) / A. georginae (Georgina gidgee) / A. argyrodendron (blackwood) dominated associations	Trough
Hughenden	Railview station	R14	-20.88119	144.65398	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Hughenden	Railview station	R15	-20.87342	144.68524	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T01	-20.78687	145.02467	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T02	-20.80505	144.99182	Non-remnant	Trough
Torrens Creek	Strathelen station	T03	-20.82846	145.00014	Non-remnant	Dam
Torrens Creek	Strathelen station	T04	-20.82758	144.97136	Non-remnant	Dam

Location	Property	Site	Latitude	Longitude	RE description	Water source
Torrens Creek	Strathelen station	T05	-20.80024	144.9652	Wetlands associated with permanent lakes and swamps, as well as ephemeral lakes, claypans and swamps. Includes fringing woodlands and shrublands	Dam
Torrens Creek	Strathelen station	T06	-20.78052	144.97155	Wetlands associated with permanent lakes and swamps, as well as ephemeral lakes, claypans and swamps. Includes fringing woodlands and shrublands	Dam
Torrens Creek	Strathelen station	T07	-20.76757	144.98074	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Dam
Torrens Creek	Strathelen station	T08	-20.76692	144.97195	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T09	-20.74025	144.97464	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T10	-20.72231	144.97632	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T11	-20.73221	145.00551	Non-remnant	Dam
Torrens Creek	Strathelen station	T12	-20.71963	145.00681	Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains/ Eucalypt dry woodlands on inland depositional plains	Dam
Torrens Creek	Strathelen station	T13	-20.69565	144.97254	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T14	-20.66718	144.93521	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Trough
Torrens Creek	Strathelen station	T15	-20.74151	144.94162	Eucalypt dry woodlands on inland depositional plains/Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains	Dam

## Camera traps

A total of 45 camera traps were deployed for two years (2022-2024) across our three study locations (fifteen sites at each location). Camera trap sites were selected based on available water points. Most cameras were located near permanent stock troughs and dams while a few were positioned near semi-permanent channels or creeks. Cameras were positioned to include the water point in the camera frame if possible, mounted on trees at a height of approximately 1.8 m (to reduce interference from stock), and angled downwards. All camera traps were Swift Enduro powered by solar panels and were set on timelapse mode to take an image every 30 minutes. Camera traps were serviced every 4-6 months where the operation of the camera was checked and maintained, and SD cards were collected.

Camera data analysis was completed using a mixed approach of AI and manual identification. Images were run through the AI 'Mega detector' function within the software application 'Timelapse' (Greenberg 2024) which identified images that were either empty or contained animals, vehicles or persons. Images that were flagged to contain animals were then viewed manually and identified to species level. Images that contained more than one species were duplicated and a separate record created. Images that were flagged as empty were then screened using the fast forward function to confirm that they were empty.



Figure 20 Camera trap setup (G. Young).



Figure 21 Example of a seasonal creek at Morven (G. Young).

## Acoustic recorders

Acoustic recorders were placed at some camera trap locations (36 sites in total, 12 per location). Recorders were placed on the same tree or a short distance from camera traps, mounted on trees at a height of approximately 1.8 m, and positioned so that the solar panel faced north (Figure 22). The solarBARS acoustic recorders were set to record at 30 min on and 30 min off intervals repeatedly (total of 12 hrs per day), at 50db, with a sampling rate of 44.1 kHz. audio data as FLAC files of 30-minute duration at a sampling rate of 96 kHz. Following collection, acoustic data were stored in the Ecosounds

acoustic data repository, hosted by the Queensland University of Technology (<https://www.ecosounds.org/>).

## Squatter pigeon call detection

### Target species and call

The vocal repertoire of the squatter pigeon includes a contact call consisting of one to six soft notes, commonly described as 'ooooo-ooooo', often with a slightly descending frequency (Figure 23A and B; BirdLife Australia, 2023; Provost, 2023). In addition, squatter pigeons produce a louder display call, the 'coo', which begins with a downward sweep in frequency followed by a strong upward inflection (Figure 23C and D; BirdLife Australia, 2023; JVO pers. obs.). These vocalizations occur within a relatively narrow frequency range of 300 to 560 Hz (Provost, 2023; JVO pers. obs.). Distinguishing features of squatter pigeon calls, compared to those of similar-sounding pigeon species, include a characteristic U- or L-shaped inflection pattern, in contrast to the inverted V-shaped inflection of crested pigeon calls (Provost, 2023). Squatter pigeon calls also have shorter syllable durations and occur at higher frequencies than those of the common bronzewing, which typically vocalises at 200–300 Hz (Provost, 2023).



Figure 22 Acoustic recorder setup (G. Young).

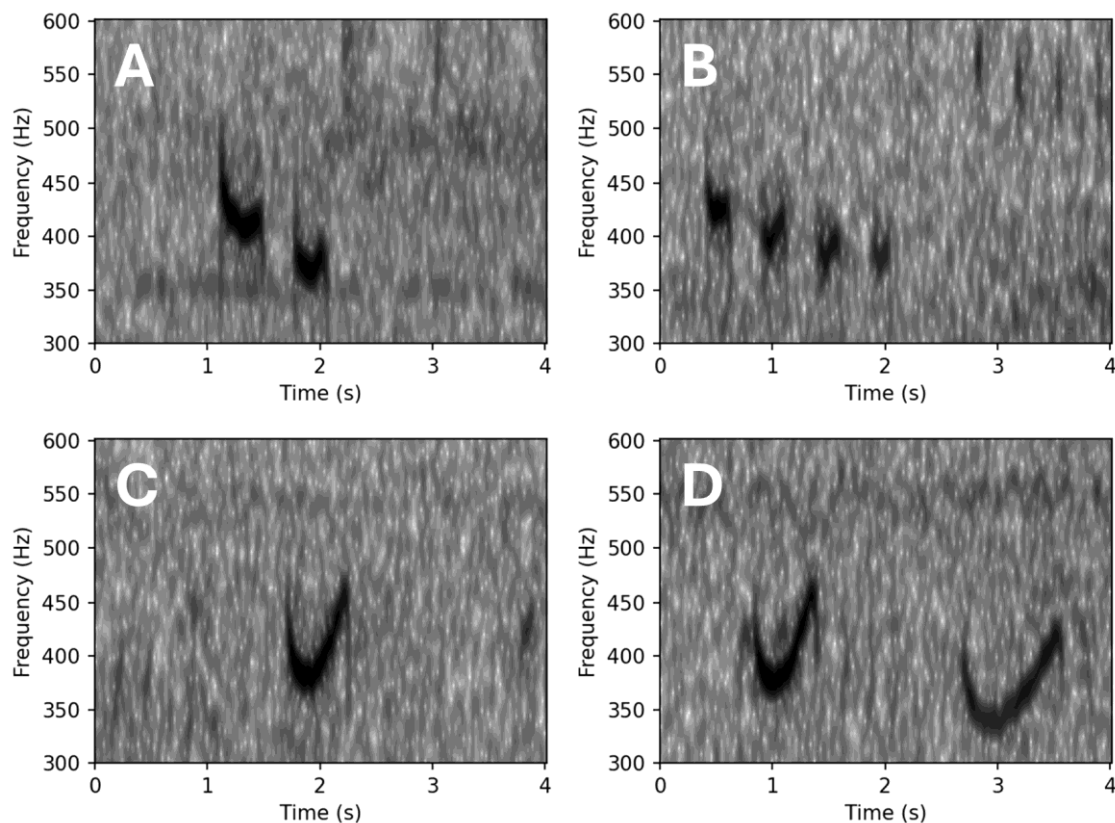


Figure 23. Example spectrograms of the target southern squatter pigeon calls, including two and four syllable variants of the contact call (A and B, respectively) and one and two syllable variants of the display call (C and D, respectively).

## Spectrogram transformation

We converted audio data to spectrograms using a 4 second frame window, with a 50% overlap between successive frames. The target calls of the squatter pigeon generally ranged from 0.5–2 seconds in duration, ensuring that target calls would be entirely included within at least one audio frame (Kahl *et al.*, 2021). The spectrogram transformation used a short-time Fourier transform, with a mel-scaled frequency axis, Hann window length of 4096 and 224 mel filter banks. Frequency limits of 300 Hz to 560 Hz were chosen following a vocalisation study on the species (Figure 23; Provost, 2023).

## Convolutional Neural Network

We developed a Convolutional Neural Network (CNN) by fine-tuning a pre-trained ResNet-34 model (He *et al.*, 2016). Model training was undertaken using the Pytorch package (version 1.10) in Python (version 3.6.9, Python Foundation). Model training was undertaken using three iterations using an active learning approach (van Osta *et al.*, 2023; Kath *et al.*, 2024). An initial coarse model was developed using handheld recordings of squatter pigeon made outside of the study area. From these handheld recordings, 223 squatter pigeon calls and 306 non-target sounds were extracted into 4 second audio frames. We then undertook three iterations of model improvement: 1) using 28.5 hours of randomly selected audio from two sites (R06 and T08), where squatter pigeon were known to be common; 2) using 48 hours of continuous audio from R06 to include nocturnal data into the model; and 3) using 17 hours of data selected randomly across all sites within the study area (30 minutes per site). A 70:30 training:validation split was used during the iterative model development to understand performance improvements. The training and validation data were combined in the final model training, which in total used 532 frames of squatter pigeon calls and 708 frames of non-target audio.

The final model was trained using a batch size of 128 and 20 epochs. We optimised learning rate using an Adam optimiser algorithm with an exponential learning rate decay function. We also accounted for the slight imbalance of our training dataset through oversampling with the `WeightedRandomSampler` function in Pytorch to account for the imbalance (Buda, Maki and Mazurowski, 2018).

The effect of incorporating site data into the model training is expected to be negligible considering only 93 hours of site recordings were included within the training, out of the total dataset of 288,460 hours.

## Model evaluation

Performance of the CNN model was evaluated by randomly selecting 20 x 30 minute files for manual review that were predicted by the model to contain at least one squatter pigeon call. The model results were then manually reviewed (JVO) to categorise each 4 second audio frame as either containing a squatter pigeon call or not containing a squatter pigeon call. Audio frames that the human annotator was uncertain as to whether they contained a squatter pigeon call were given an 'uncertain' label and excluded for the purpose of evaluation metrics. We then calculated standard evaluation metrics (Stowell, 2022).

All audio frames were reviewed by visualizing each 4-second segment as a spectrogram filtered to the 300–560 kHz range. Audio was also played back both in its full frequency range and with a band-pass filter applied to the 300–560 kHz range to eliminate non-target noise. To analyse acoustic data we developed a Convolutional Neural Network (CNN) by fine-tuning a pre-trained ResNet-34 model (He *et al.*, 2016). Performance of the CNN model was evaluated by randomly selecting 20 x 30 minute files for manual review that were predicted by the model to contain at least one squatter pigeon call. The model results were then manually reviewed to categorise as either containing a squatter pigeon call or not containing a squatter pigeon call. To determine the sites at which squatter pigeon were present or absent, the top 100 model scores, ranked by the prediction confidence, were manually reviewed. Reviewing the top 100 predictions from each site gives a high confidence that squatter pigeon calls would be detected if present in the audio (Allen-Ankins, Laguna and Schwarzkopf, 2024).



Figure 24 Artificial water sources where squatter pigeon monitoring sites were located (G. Young).

### Relative abundance

Squatter pigeon relative abundance was calculated simply by graphing detections per camera per week over time to show long term fluctuations, and detections per site to show site level differences in squatter pigeon abundance.

### Landscape habitat characteristics

To identify habitat landscape characteristics influencing squatter pigeon patch use at key sites we performed a landscape analysis. All steps for landscape data extraction and analysis are the same as those outlined in the yakka skink methods above.

### Results

Cameras recorded a total of 8,667 squatter pigeons during the study (Table 5). The majority of these detections were from the two northern study locations Hughenden and Torrens Creek, both of which recorded a similar number of squatter pigeon detections ( $n = 4,219$  and  $n = 4,410$  respectively). The southern location, Morven, only recorded 38 squatter detections. In comparison to other least concern pigeon and large dove species such as the common bronzewing, crested pigeon and bar shouldered dove, squatter pigeon numbers compare favourably at the northern study locations (Table 5). To the south, however, squatter detections are notably lower than other species.

Table 5 Squatter pigeon camera detections in comparison to three other pigeon species at each location.

Location	Squatter pigeon	Common bronzewing	Crested pigeon	Bar shouldered dove
Morven	38	4,472	404	82
Hughenden	4,219	213	8,189	6
Torrens Creek	4,410	1,009	706	27
<b>Total</b>	<b>8,667</b>	<b>5,694</b>	<b>9,299</b>	<b>115</b>

### Call detection model evaluation

The call detection model achieved an area under the precision-recall curve (AUC = 0.93), indicating strong overall discriminative ability between true squatter pigeon calls and non-target sounds (Figure 25). The highest F1 score, indicating the best balance between precision and recall, was achieved at a confidence threshold of 0.55 (precision = 0.841, recall = 0.812, F1 = 0.826). False positives were nearly eliminated at a confidence threshold above 0.95 (precision = 0.998, recall = 0.408, F1 = 0.57), while false negatives were nearly eliminated at a confidence threshold below 0.06 (precision = 0.449, recall = 0.992, F1 = 0.619). There were two main calls that contributed to the false positives, which were of a similar shape and frequency range to squatter pigeon. These were the pheasant coucal (*Centropus phasianinus*) and the southern boobook owl (*Ninox boobook*).

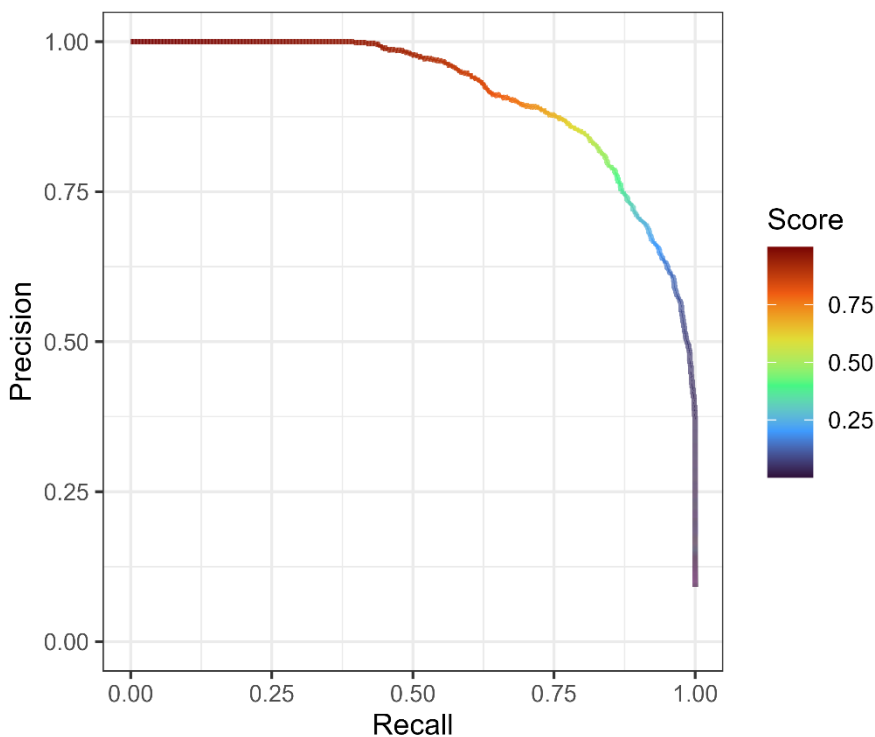


Figure 25 Precision-recall curve for the squatter pigeon call detection model. Scores were calculated using the logit produced by the call detection model transformed to a scale of 0 to 1 with a sigmoid transformation. Scores closer to 1 are predicted by the call detection model as more likely to be a squatter pigeon call, while scores closer to 0 are more likely to be other sounds.

## Detection patterns of squatter pigeon

There was large variation in the average number of calls per day among the sites where squatter pigeon were recorded (Figure 26), and substantial seasonal variation in the calls per day (Figure 27). Calls were lowest in January and had bimodal peaks in April and September. Call activity also varied by time of day (Figure 28), with a morning peak that had a maximum call rate and declined to a broad plateau of approximately 16 calls per hour from the late morning to the late afternoon.

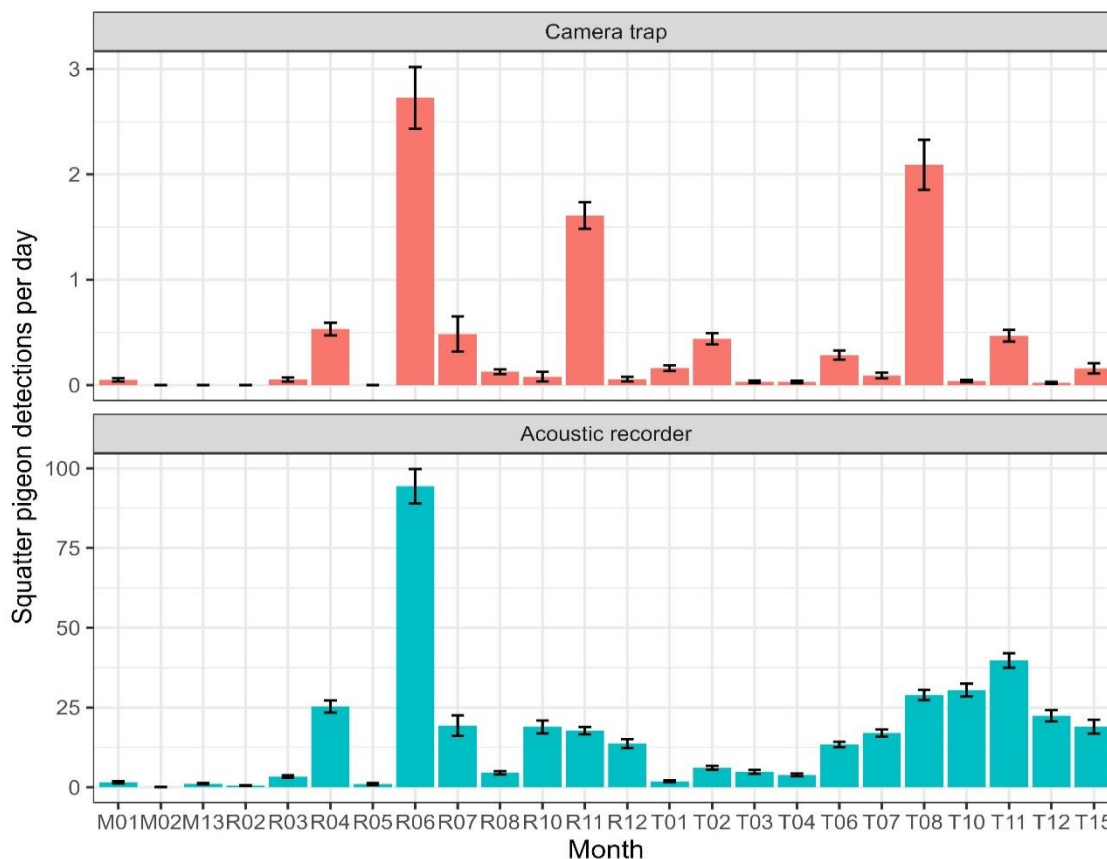


Figure 26: Average number of calls per day among the sites where squatter pigeon calls were detected.

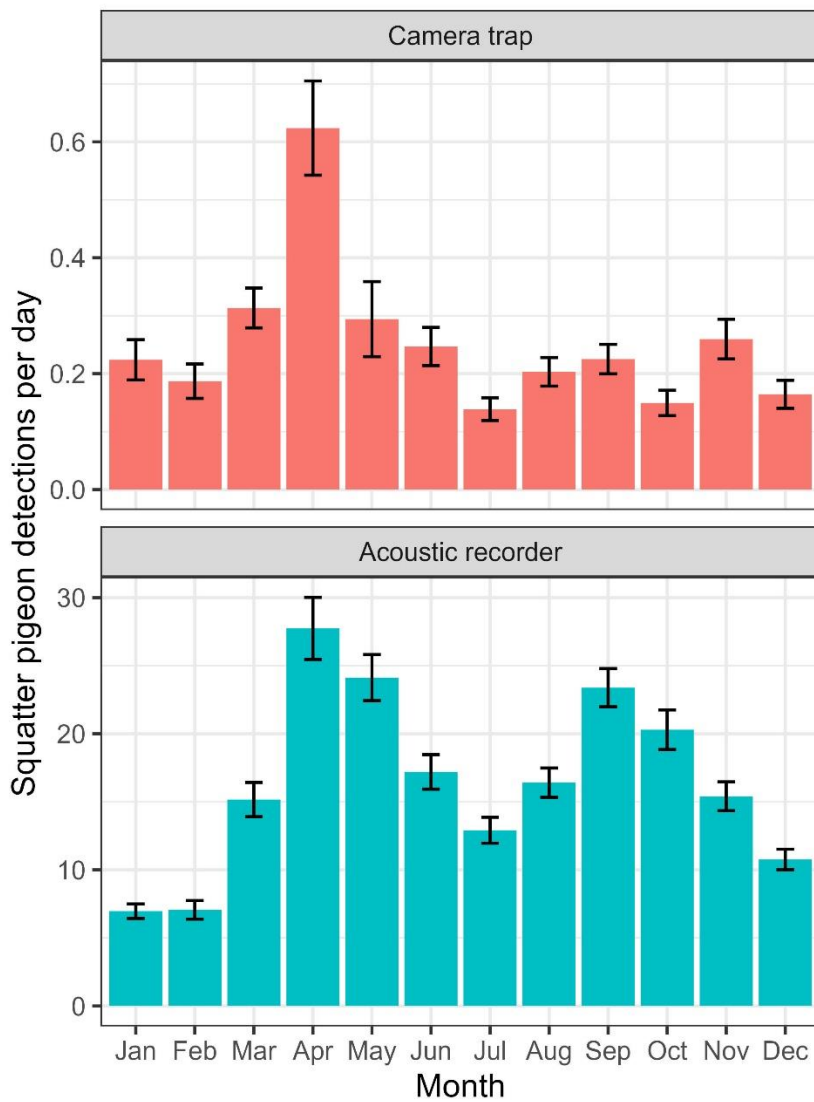


Figure 27: Monthly average squatter pigeon detections per day from camera traps (top) and acoustic recorders (bottom). Bars show standard error around the mean.

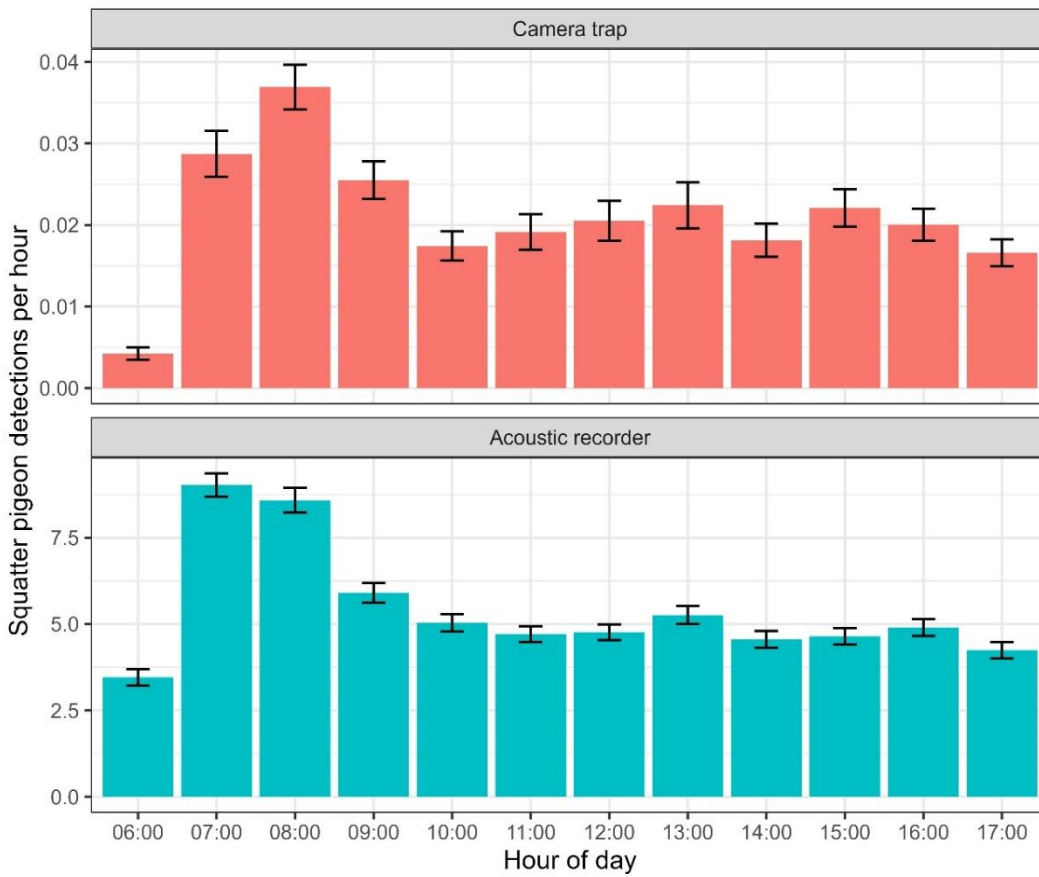


Figure 28: Average number of squatter pigeon calls detected per hour. Bars show 95% confidence intervals calculated using bootstrapping.

### Comparison of acoustic recorder to camera trap detection rates

There was a strong correlation between the site-level detection rates of camera traps and acoustic recorders, as measured by the proportion of days that contained a detection ( $\beta = 0.346$ , 95% CI: 0.174–0.519, Figure 29). The average proportion of days with a squatter pigeon detection was substantially higher for acoustic recorders (mean = 0.279, 95% CI: 0.230–0.334) than for camera traps (mean = 0.053, 95% CI: 0.036–0.078). The detection rates of both methods increased in proportion to the site-level abundance of squatter pigeon ( $\beta = 0.163$ , 95% CI: 0.114–0.211) (Figure 29).

Acoustic recorders required the smallest number of survey days required to achieve a 95% confidence of detecting squatter pigeon, which ranged from 2.04 days (95% CI: 1.53–2.88) where the species was most abundant to 26.5 days (95% CI: 17.9–39.6) where the species was least abundant (Figure 29). In comparison, camera traps required 8.06 days (95% CI: 4.98–13.6) where the species was most abundant and 169 days (95% CI: 91.2–314) where the species was least abundant (Figure 29).

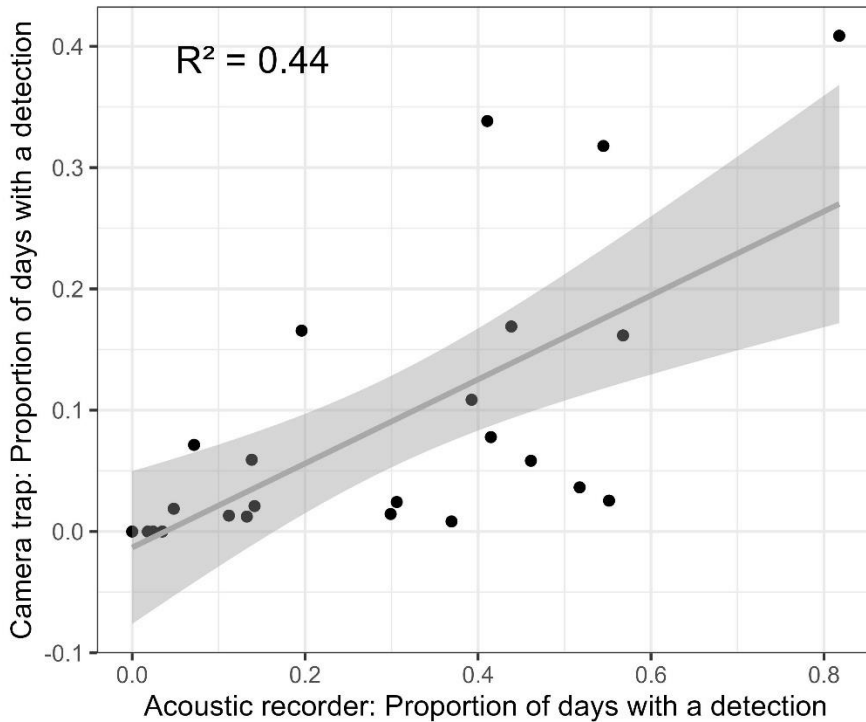


Figure 29: Comparison of site-level detection rates between camera traps and acoustic recorders.

### Relative abundance

Squatter pigeon detections varied over time (Figure 30). The highest number of detections (>300 pigeon detections per week) were recorded at Hughenden at the beginning of the study around April 2022. Detections were similarly high for Torrens Creek around May 2022. Following this, detections dropped suddenly at both locations then displayed a pattern of seasonal peaks and troughs that typically ranged from 0 to 100 pigeon detections per week. These peaks and troughs do not seem to correspond with a particular season. Hughenden and Torrens Creek recorded a similar number of detections and followed a similar pattern, while Morven recorded very few squatter pigeon detections.

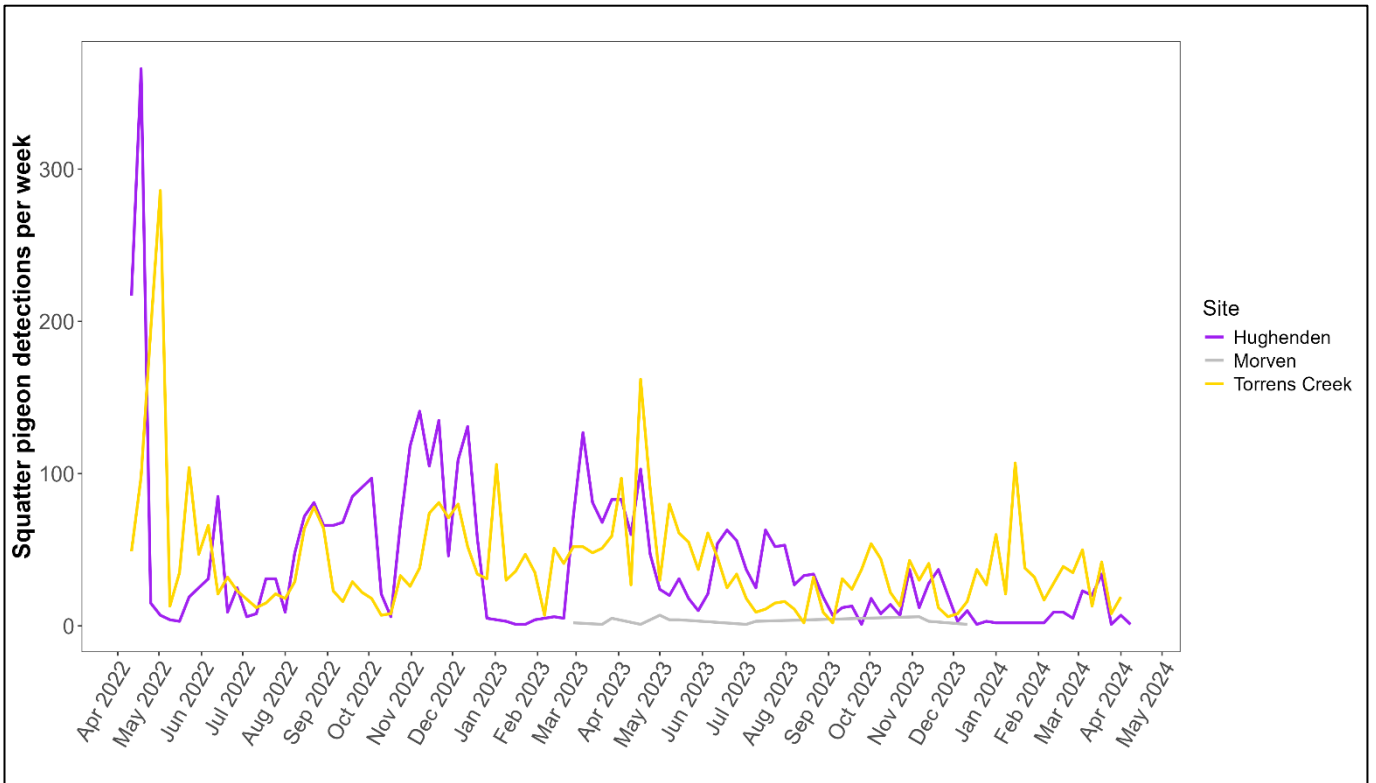


Figure 30 Squatter pigeon detections on camera traps over time at Morven, Hughenden and Torrens Creek.

At Morven only two monitoring sites recorded squatter pigeons (M01 and M05), and only a few detections were ever recorded (Figure 31). At Hughenden, 11 of 15 monitoring sites recorded squatter pigeons, though some recorded more than others – R06, R011, and R014 consistently recorded squatter pigeons throughout the study (Figure 32). At Torrens Creek, 14 of 15 monitoring sites recorded squatter pigeons with T08 and T09 consistently recording high numbers throughout the study (Figure 33).

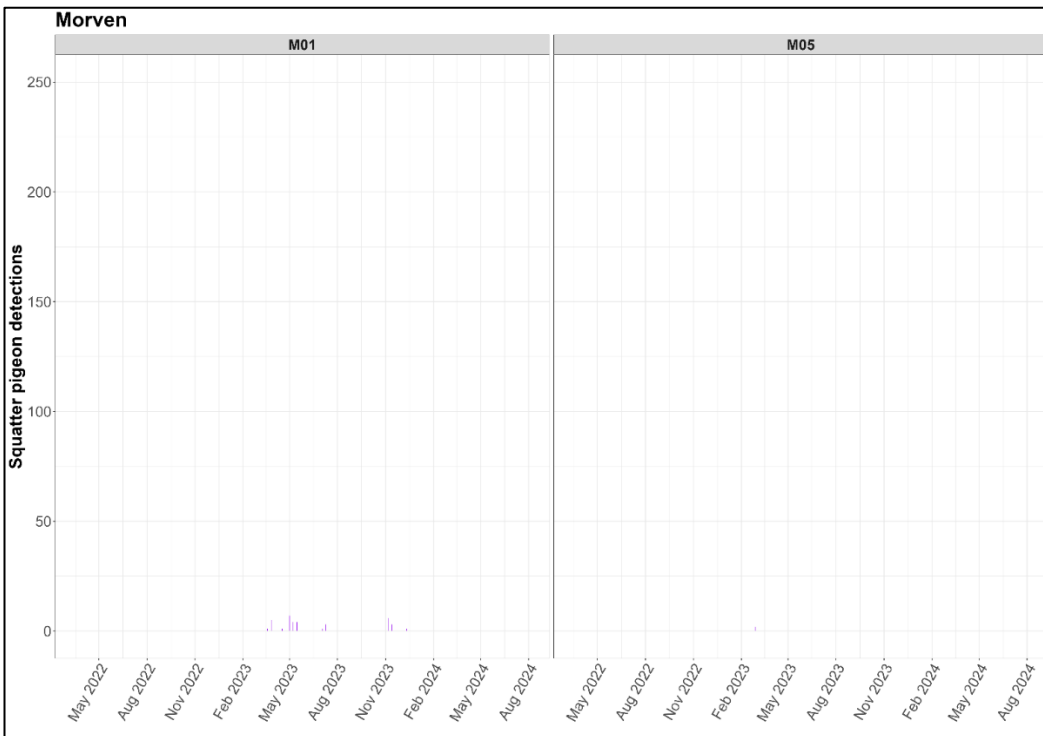


Figure 31 Squatter pigeon detections per camera at Morven.



Figure 32 Squatter pigeon detections per camera at Hughenden.

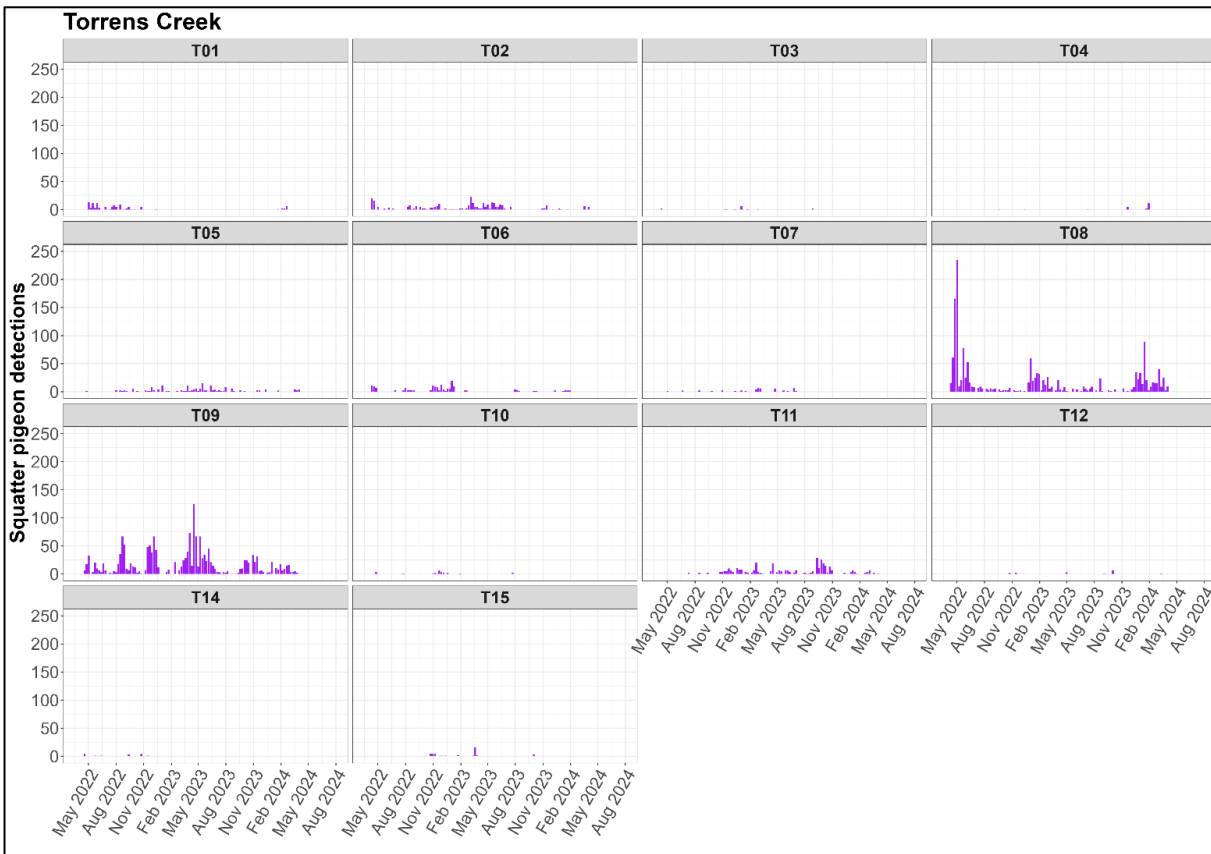


Figure 33 Squatter pigeon detections per camera at Torrens Creek.

### Effects of grazing

Cattle presence had a positive effect on squatter pigeon presence (0.07) (Figure 34). It also had a small confidence interval around the estimate. When plotted against each other, cattle (log scale) and squatter pigeon (log scale) weekly detections followed a similar trend (Figure 34). This is particularly apparent at Hughenden and Torrens Creek where there were sufficient squatter pigeon records. There are three obvious troughs in weekly detections of cattle at Hughenden in mid-2022 and early 2023 and one large trough at Torrens Creek around August 2023. Squatter pigeon detections likewise experienced a large dip around the same time or just after cattle detections fell. Similarly, peaks in cattle detections correspond with peaks in squatter pigeon detections.

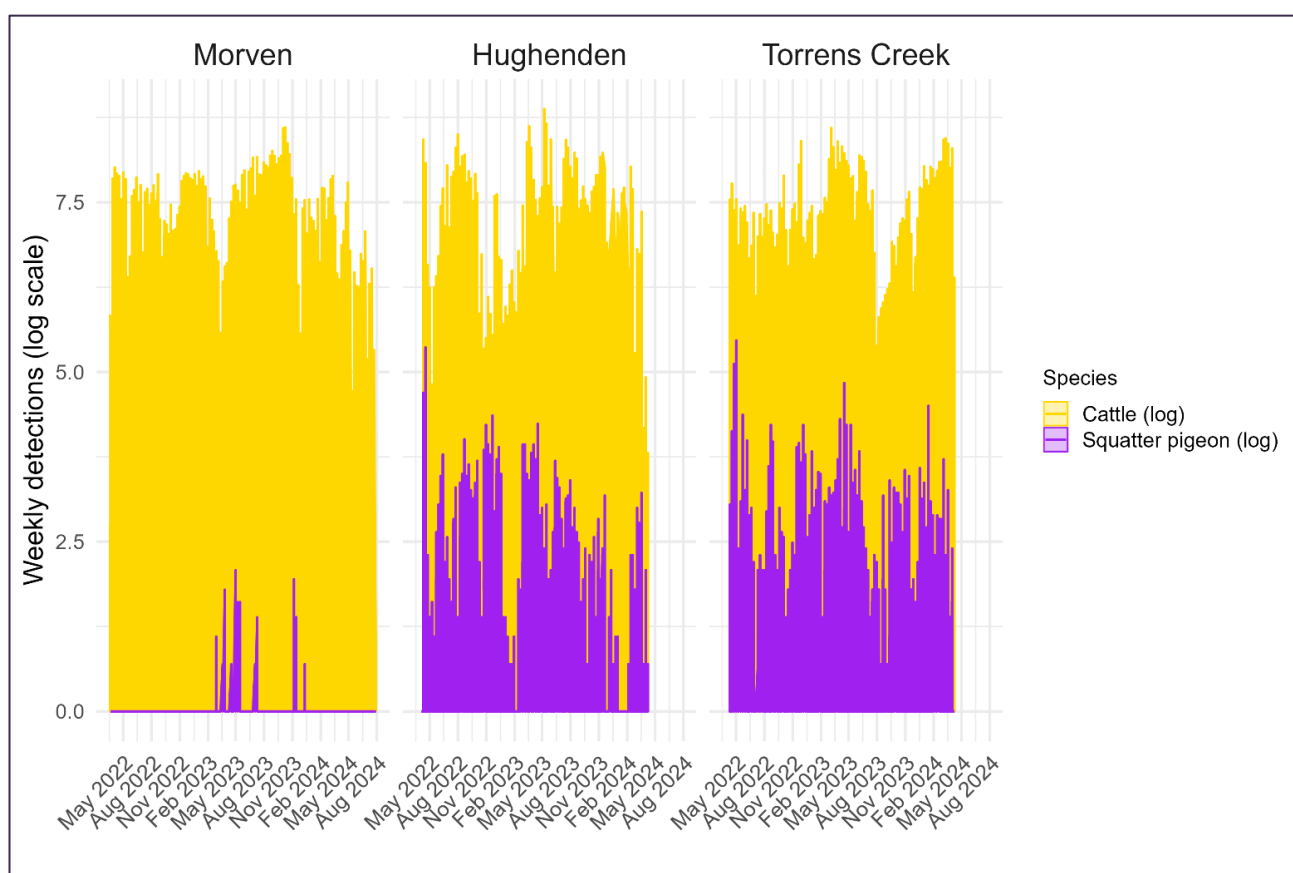


Figure 34 Weekly detections (log scale) of cattle and squatter pigeons at each study location.



Figure 35 A squatter pigeon in a dry, over grazed landscape.

### Effects of invasive species

Foxes were only recorded on camera at Morven, while feral cats and wild dogs were present at all three study locations (Table 6). Detections of feral cats ( $n = 38$ ) and foxes ( $n = 16$ ) were relatively low, while wild dog detections were notably higher ( $n = 447$ ). Feral pigs were present at all three locations and detections were very high ( $n = 10,378$ ). The structural equation model showed that fox and feral cat presence had a negative effect on squatter pigeon presence ( $-0.31$  and  $-0.16$  respectively), while feral pigs and wild dogs had a slight positive effect ( $0.03$  and  $0.05$  respectively) (Figure 38).

Table 6 Camera detections of invasive predators at each study location.

Location	Feral cat	Wild dog /Dingo	Fox	Feral pig
Morven	15	216	16	1,596
Hughenden	9	85	0	1,197
Torrens Creek	14	146	0	7,585
<b>Total</b>	<b>38</b>	<b>447</b>	<b>16</b>	<b>10,378</b>

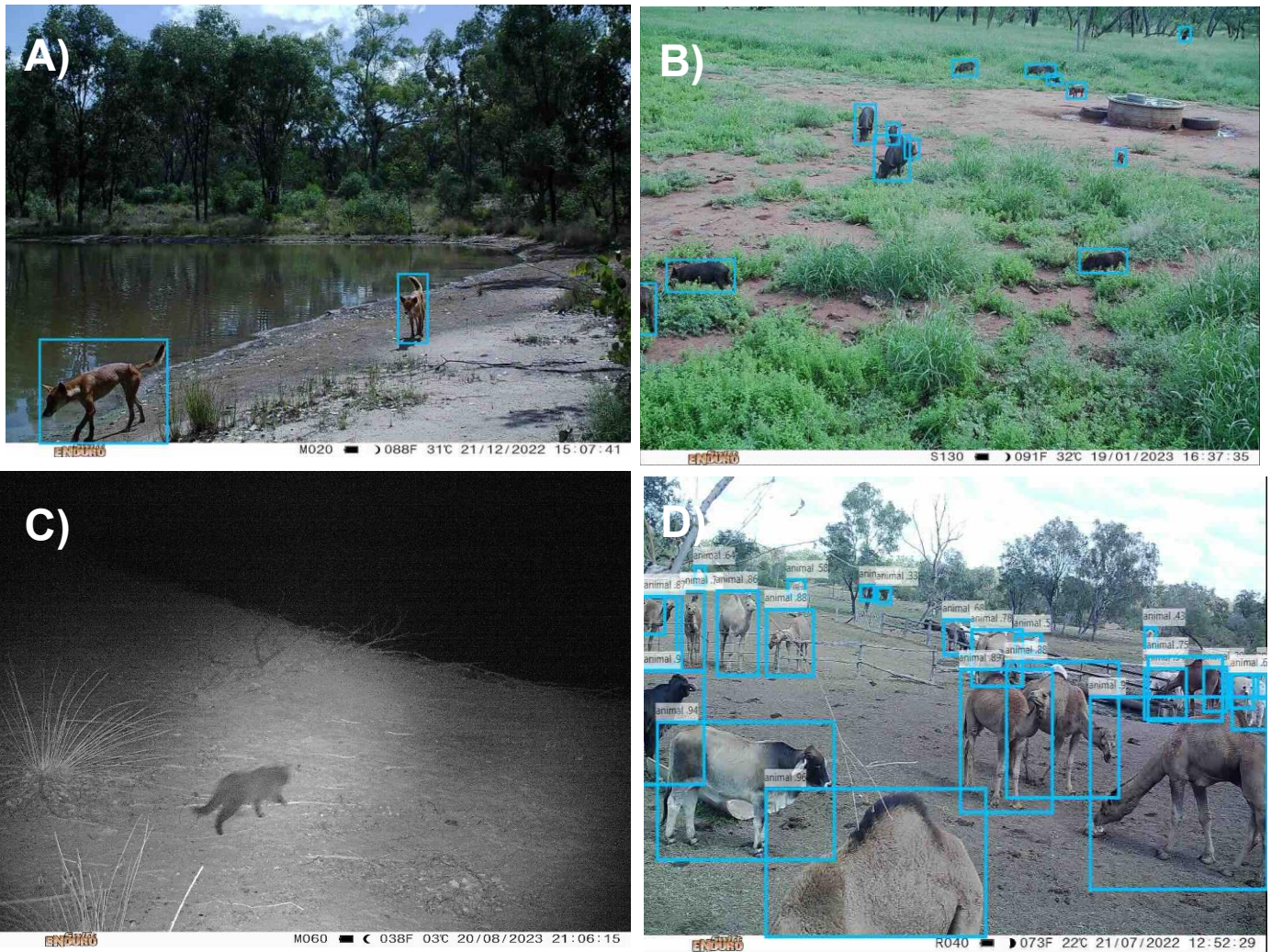


Figure 36 Camera trap images of invasive species A) wild dogs / dingoes, B) feral pigs, C) feral cat, D) camels and cattle.

### Structural equation model- landscape level

The strongest positive effect was from monthly minimum temperature  $\rightarrow$  mean\_mavi (0.68), highlighting that warmer minimum temperatures significantly increase vegetation productivity. Mean treecover\_2024  $\rightarrow$  mean\_mavi (0.20) and monthly minimum temperature  $\rightarrow$  treecover\_2024 (0.12) also have moderate positive effects, showing the role of forest cover and temperature in enhancing vegetation.

A series of small positive effects follow, with cattle presence  $\rightarrow$  pigeon presence (0.07), dog presence  $\rightarrow$  pigeon presence (0.05), pig presence  $\rightarrow$  pigeon presence (0.03), and monthly maximum temperature  $\rightarrow$  pigeon presence (0.03), suggesting these factors offer weak but positive contributions to pigeon occurrence. Neutral to weak negative effects are seen from monthly minimum temperature  $\rightarrow$  pigeon presence (0.00), mean\_mavi  $\rightarrow$  pigeon presence (-0.01), and various other predictors with coefficients between -0.02 and -0.11. These include factors such as rainfall, clay content, and tree cover, indicating minimal or inconsistent influence. Stronger negative effects begin with cat presence  $\rightarrow$  pigeon presence (-0.16), clay content  $\rightarrow$  pigeon presence (-0.18), and fire presence  $\rightarrow$  pigeon presence (-0.25). Fox presence  $\rightarrow$  pigeon presence shows a more substantial negative effect (-0.31), indicating predation pressure. The strongest negative effects overall are from monthly rainfall  $\rightarrow$  mean\_mavi (-0.33), monthly

maximum temperature → mean\_mavi (-0.34), and monthly maximum temperature → treecover\_2024 (-0.70). This suggests that high maximum temperatures and increased rainfall strongly reduce vegetation productivity and forest cover, which in turn indirectly reduce pigeon habitat suitability.

In summary, vegetation productivity (mean\_mavi) is most positively influenced by minimum temperature and forest cover, while pigeon presence is most negatively affected by high temperatures and predation (especially foxes).

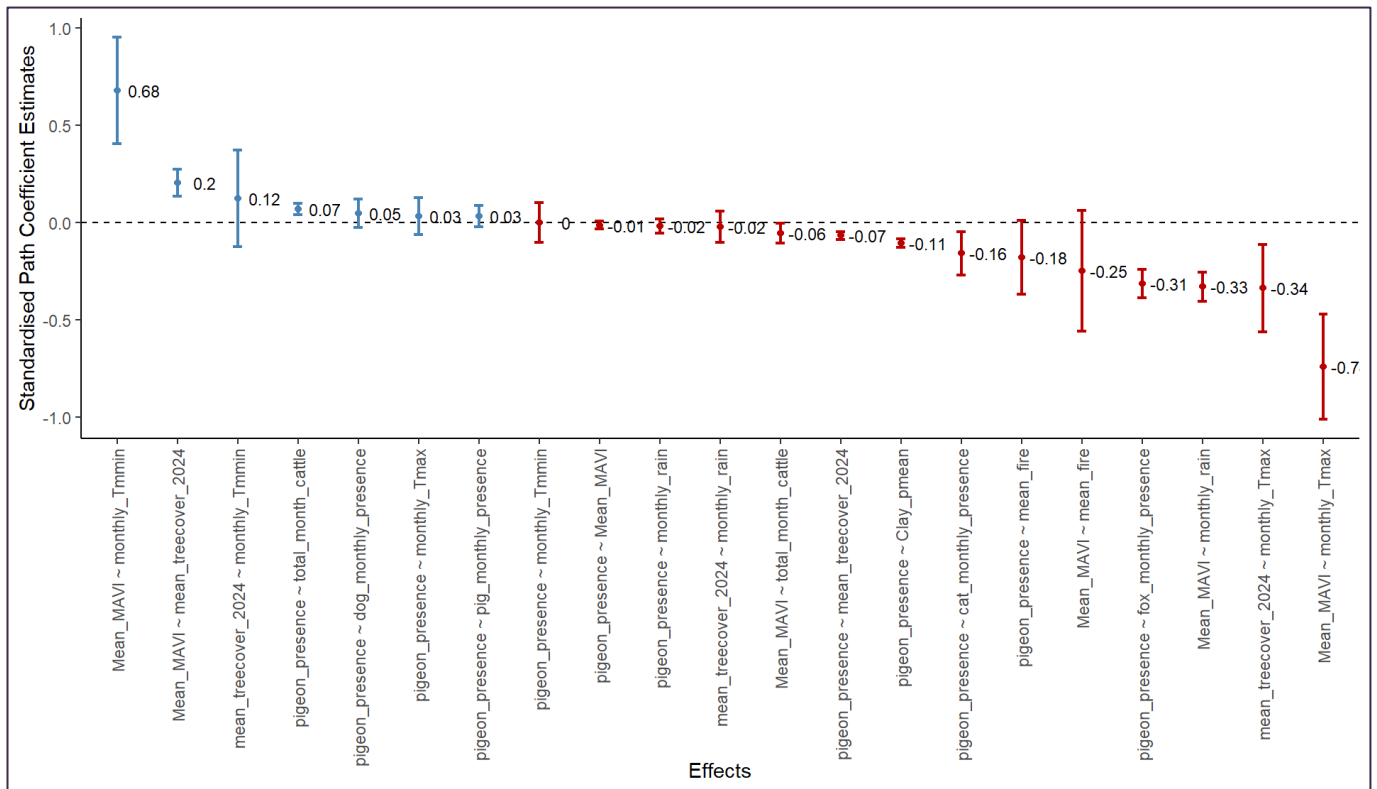


Figure 37 Standardised path coefficients of the squatter pigeon structural equation model, ordered from strongest positive effect to strongest negative effect. The intervals shown are the 95% confidence intervals about the estimate.

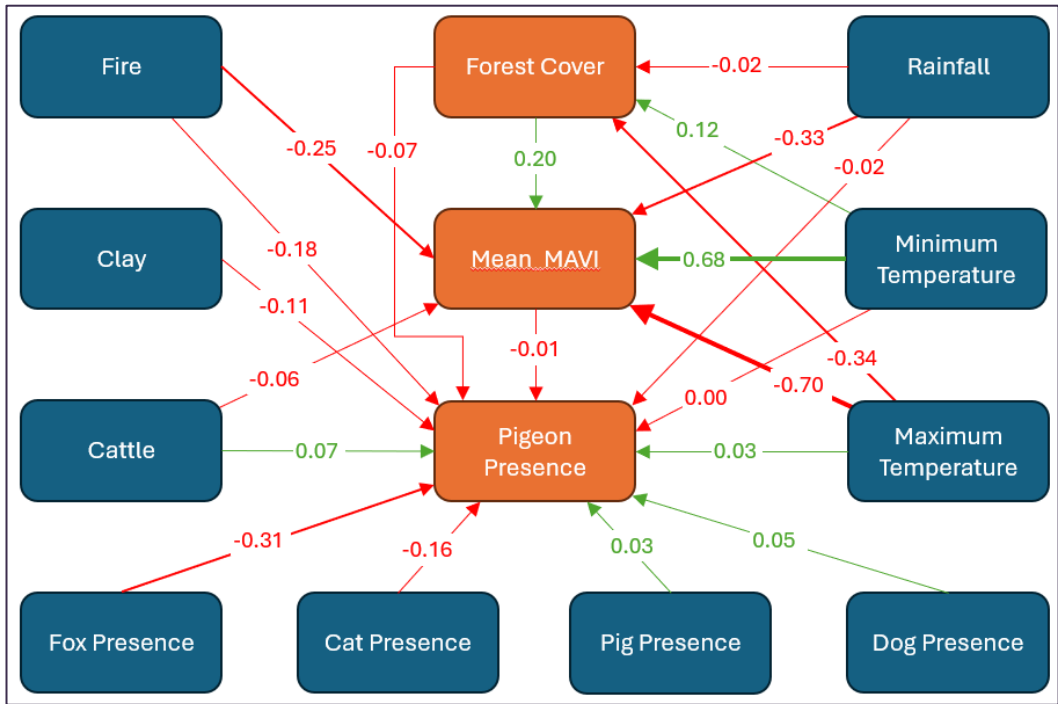


Figure 38 Path diagram of the squatter pigeon structural equation model showing the directed paths and their associated path coefficients. The blue boxes are the exogenous variables, and the orange boxes are the endogenous variables. Red paths indicate a negative direct effect, green indicates a positive direct effect.

The ROC plot, which evaluates the performance of a binary classifier by plotting sensitivity against 1-specificity. The blue curve represents the classifier's performance, while the diagonal grey line indicates a random guess (AUC = 0.5). With an Area Under the Curve (AUC) of 0.7674 (Figure 39), the model demonstrates good discriminative ability, meaning it can effectively distinguish between the two classes to predict squatter pigeon habitat suitability at the landscape scale.

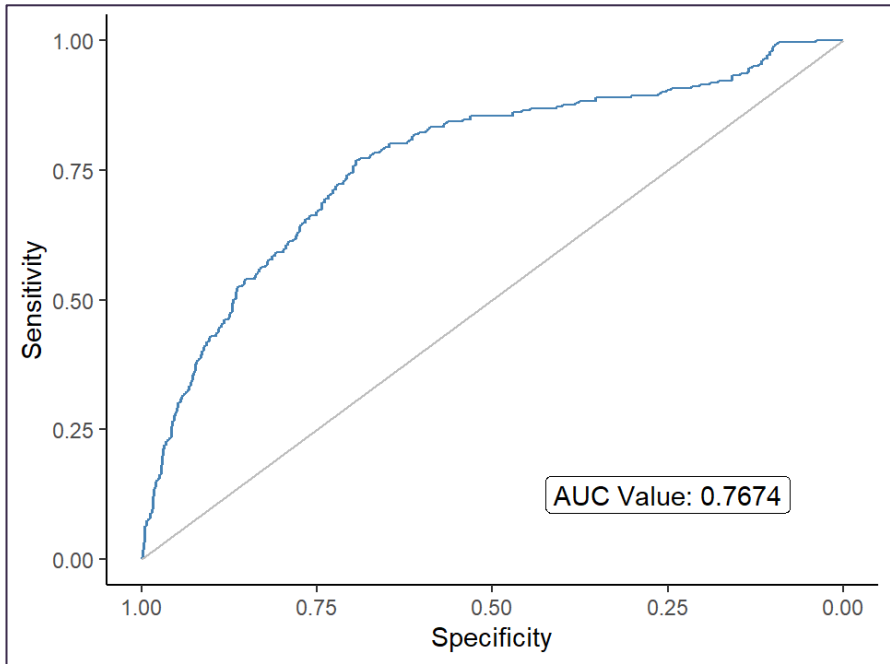


Figure 39 Receiver operating characteristic plot for the squatter pigeon landscape level structural equation model. AUC values near 1 represent a model with a strong ability to correctly distinguish pigeon presence, while values

*near 0.5 represent a model with no capacity. AUC values near 0 indicate a poor predictive ability to identify pigeon presence, where values are more incorrectly predicted than if they were chosen at random.*

## Discussion

The results of this study provide valuable insight into the distribution, detectability, and environmental drivers influencing squatter pigeon presence across a broad landscape. The stark contrast between the high number of detections in the northern study areas (Hughenden and Torrens Creek) and the extremely low detections in the southern site (Morven) highlights a distinct regional pattern in abundance. The combined use of camera traps and acoustic recorders illustrated that squatter pigeons are more active and more widely distributed in the north, with very limited presence in the south. Monthly averages from both detection methods closely aligned, reinforcing the reliability of the findings across different data collection techniques. During the study, a total of 8,667 squatter pigeons were recorded on camera traps across three sites. The vast majority of detections occurred at the two northern locations, Hughenden and Torrens Creek, which recorded 4,219 and 4,410 squatter pigeon detections respectively. In contrast, the southern location, Morven, yielded only 38 detections. When compared to three other commonly recorded large pigeon and dove species—the common bronzewing, crested pigeon, and bar-shouldered dove—squatter pigeons were relatively abundant at the northern sites. However, they were notably less common in the south, where species like the common bronzewing were far more frequently detected.

Over time, squatter pigeon detections showed seasonal fluctuations at the northern locations, with initial peaks of over 300 detections per week during April and May 2022, followed by a decline and the emergence of irregular seasonal peaks and troughs. Patterns at Hughenden and Torrens Creek were similar, both in detection numbers and temporal variation, while Morven showed very limited activity. At the site level, Morven only recorded pigeons at two locations, while most sites at Hughenden and Torrens Creek recorded pigeons regularly. In particular, sites like R06, R011, and R014 at Hughenden and T08 and T09 at Torrens Creek consistently recorded high activity. Acoustic data further supported these spatial trends, showing higher calling rates at the northern sites.

Acoustic recorders were deployed across the study sites to detect vocalisations of squatter pigeons, enabling continuous monitoring of calling behaviour across day and night and during periods when visual detections may be limited due to vegetation cover or light conditions. This method proved particularly useful for detecting birds in areas where camera detections were infrequent or absent.

Across the 24 sites where squatter pigeon calls were detected, the average number of calls per day revealed a clear spatial trend that aligned with the camera trap results. The northern sites—Hughenden and Torrens Creek—recorded the highest calling rates, further supporting the conclusion that these areas support higher population densities and more consistent activity. In contrast, Morven recorded very few calls, confirming its comparatively low squatter pigeon presence. The acoustic data helped to detect presence even at times or locations where pigeons may not have triggered cameras, thus strengthening confidence in site-level occupancy assessments.

Temporal analysis of acoustic data showed seasonal variability in vocal activity, with monthly averages displaying a pattern of peaks and troughs that generally matched trends observed in camera detections. This convergence between data types reinforces the validity of the findings and suggests that calling behaviour may be linked to broader environmental or behavioural cycles, such as breeding or foraging activity. However, like the camera data, these acoustic peaks did not align with a single distinct season, indicating that squatter pigeon calling behaviour may be driven by more complex or site-specific cues rather than broad seasonal changes.

In summary, the acoustic analysis expanded the scope and resolution of monitoring by providing a non-invasive, continual method for detecting squatter pigeon presence. It was particularly effective in

corroborating the regional differences in abundance, identifying active sites, and capturing temporal fluctuations in activity that were consistent with the camera trap data. Acoustic monitoring proved to be a more effective detection method than camera trapping, with a higher detection rate and fewer survey days required to confidently detect the species. This efficiency is particularly valuable in low-abundance areas, where the time and cost required for detection using camera traps are much higher. The strong correlation between detection rates from both methods supports the validity of using acoustic data as a proxy for abundance.

Structural equation modelling revealed that most habitat characteristics had little to no significant effect on squatter pigeon presence. Mean MAVI and forest cover showed only a slight negative effect. Climatic variables similarly had minimal impact; maximum temperature had a small positive effect, while rainfall and minimum temperature had negligible or no effect. These results suggest that traditional habitat quality metrics may not be strong predictors of squatter pigeon distribution across these sites and site-specific attributes drive presence and abundance.

In contrast, the presence of cattle had a positive association with squatter pigeon presence. Weekly detections of cattle and squatter pigeons followed a similar trend at the two northern sites, particularly at Hughenden and Torrens Creek. Periods of reduced cattle activity were often followed by reductions in squatter pigeon detections, while peaks in cattle presence generally corresponded with increased pigeon detections. This suggests that cattle grazing may create or maintain open ground conditions that are favourable to squatter pigeons, which are known to prefer sparsely vegetated habitats for foraging and movement.

The study also examined the role of invasive species on squatter pigeon occurrence. Feral cats and wild dogs were present across all three sites, but foxes were only detected at Morven. While the number of feral cat and fox detections was low, the structural equation model indicated that their presence had a negative effect on squatter pigeons. Feral cats had a path coefficient of -0.16, and foxes had a stronger negative effect at -0.31. Despite the extremely high number of feral pig detections—over 10,000 across the three sites—there is limited evidence from this model to suggest a strong direct effect on squatter pigeons, either positive or negative.

Overall, the study highlights a strong regional contrast in squatter pigeon abundance, with northern sites supporting much larger and more stable populations than the southern site. Grazing appears to be an important positive influence, possibly through its effects on habitat structure. Meanwhile, invasive predators—especially foxes and feral cats—pose potential threats.

## **Management recommendations**

### **Prioritize northern regions for conservation**

Squatter pigeons were significantly more abundant and active in the northern study areas of Hughenden and Torrens Creek compared to Morven in the south. Conservation efforts should focus on these northern regions to protect and support stable populations.

### **Adopt acoustic monitoring as a primary survey tool**

Acoustic recorders proved more effective than camera traps, offering higher detection rates and requiring fewer survey days. This method is especially valuable in low-abundance areas and should be prioritized for future monitoring programs.

### **Integrate sustainable cattle grazing practices**

Cattle presence was positively associated with squatter pigeon activity, likely due to the creation of open ground conditions favourable for foraging. Sustainable grazing should be considered as part of habitat management strategies.

### **Implement targeted predator control**

Feral cats and foxes negatively impacted squatter pigeon presence, with foxes showing a stronger effect, particularly at Morven. Targeted control of these invasive predators should be incorporated into conservation plans, especially in southern regions.

### **Future research priorities**

#### **Examine the role of grazing intensity and management**

Given the positive association between cattle presence and squatter pigeon activity, studies should assess how different grazing regimes (e.g., rotational vs. continuous grazing) affect habitat suitability and pigeon abundance.

#### **Assess predator impact**

The study indicated negative effects from feral cats and foxes, but detection rates were low. Future work should use targeted predator monitoring (e.g. scat analysis) to better understand predator-pigeon interactions and quantify predation risk.

#### **Explore breeding and foraging behaviour**

Temporal fluctuations in activity suggest potential links to breeding or foraging cycles. Research into nesting success, chick survival, and seasonal food availability could clarify these behavioural drivers.

#### **Evaluate acoustic monitoring for long-term population trends**

Given its effectiveness, acoustic monitoring could be further developed to track long-term population dynamics, detect changes in vocal behaviour, and refine occupancy models.

#### **Investigate interactions with other bird species**

Comparative studies with species like the common bronzewing and crested pigeon could reveal competitive or facilitative relationships, especially in areas where squatter pigeons are less common.

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