Northern Australia Environmental Resources Hub

National Environmental Science Programme

Monitoring, mapping and safeguarding Kimberley bilbies

Final report

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This report should be cited as:

Department of Biodiversity, Conservation and Attractions. (2021). Monitoring, mapping and safeguarding Kimberley bilbies. DBCA, Western Australia.

Cover photographs

Left: Bilby captured on remote sensor camera on Gooniyandi country (Photo Department of Biodiversity, Conservation and Attractions)
Centre: Nyikina Mangala Rangers completing bilby plots and capturing plot data (Photo Kyle Raina)
Right: Ngurrara ladies point out a fresh bilby burrow while completing occupancy surveys (Photo Bruce Greatwich)

This report is available for download from the Northern Australia Environmental Resources (NAER) Hub website at nespnorthern.edu.au

The Hub is supported through funding from the Australian Government's National Environmental Science Program (NESP). The NESP NAER Hub is hosted by Charles Darwin University.

ISBN 978-1-922684-46-2

October, 2021

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Acronyms and abbreviations

AIC............. Akaike information criterion

AUC........... Area under curve

DNA........... Deoxyribonucleic acid

PCR........... Polymerase chain reaction

SECR.......... Spatially explicit capture-recapture

Acknowledgements

The Nyikina Mangala Rangers, Ngurrara Rangers, Gooniyandi Rangers, Bunuba Rangers and Kija Rangers are acknowledged for their partnership in this project. We also thank the Traditional Owners of Fitzroy River catchment area, along with the Native Title Prescribed Bodies Corporate and Native Title Representative Bodies, including the Kimberley Land Council (KLC), Walalakoo Aboriginal Corporation, Yanunijarra Aboriginal Corporation, Gooniyandi Aboriginal Corporation, Bunuba Dawangarri Aboriginal Corporation and Kija Rangers on behalf of KLC for their support of this project and access to Country within the project area. We thank Karen Dayman (KLC) for assistance with coordination with ranger groups.

The rangers, ranger coordinators, Traditional Owners and staff who contributed to planning, project design and undertaking field surveys for this project are acknowledged as co-authors of this report.

The pastoral lessees of Myroodah, Mt Pierre, Jubilee Downs, Nerrima, Brooking Springs, Quanbun Downs, Bohemia Downs and Beefwood Park stations provided access for survey teams to enter land under their management for which we are grateful.

Martin Dziminski, Bruce Greatwich, Ruth McPhail, Tracy Sonneman, Lesley Gibson, Craig Olejnik and Stephen van Leeuwen (Western Australia Department of Biodiversity, Conservation and Attractions [DBCA]) along with Malcolm Lindsay (Environs Kimberley), assisted in the design and delivery of this project, and review of this report and associated outputs.

Project staff that coordinated and assisted with the implemention of field surveys included Bruce Greatwich, Ruth McPhail, Nicole Godfrey, Julia French, Dane Johnson, Ian Cooksey, Dayne Ivandich, Jason Johnson, Glen Murray, Martin Dziminski, Fiona Carpenter and Mark Blythman (DBCA), and Malcolm Lindsay, Jesse Alai and Andrew Moreton (Environs Kimberley).

We acknowledge the initial work on bilbies undertaken by WWF Australia and Environs Kimberley in this region.

This project was funded by the Australian Government's National Environmental Science Program through its Northern Australia Environmental Resources Hub.

Nyikina Mangala Rangers

Ngurrara Rangers

Bunuba Rangers

Gooniyandi Rangers

Kija Rangers

Executive summary

The Fitzroy River catchment project area extends from Dampier Downs Station in the west to Moola Bulla Station in the east. The southern section of the project area is believed to be part of a broader area identified nationally as a stronghold for the continued persistence of greater bilby (*Macrotis lagotis*) populations. However, no coordinated systematic surveys or monitoring of bilby populations have occurred in this area and the status of bilby populations in the Fitzroy catchment was unknown.

To address this information gap, we undertook an occupancy survey of the bilby across this area and assessed population abundance at selected locations. To better understand the extent of the potential distribution of this species, we also developed habitat suitability models.

The occupancy survey identified the probability of presence of bilbies and other key species that have been recognised as threats to bilby populations across the project area, using repeat surveys to account for imperfect detection. Bilby occupancy was estimated at 0.21 with a per survey detection probability of 0.49. There was a negative relationship between bilby occupancy and cattle occupancy. Bilby detection was influenced by a combination of vegetation type and fire frequency.

Feral cat occupancy across the project area was high at 0.91 and feral cat occupancy detected by remote cameras at bilby populations was also high at 0.8. An alarming finding was the presence of foxes at the three monitored bilby populations. Foxes have the potential to decimate bilby populations and have been implicated as the primary reason for the disappearance of bilbies from the southern portion of their former range. Foxes were detected at two bilby populations by remote cameras, and at a third on a nearby sign plot. Fox occupancy derived from cameras was 0.23 across the three bilby populations. Foxes and feral cats were commonly recorded on remote cameras stationed at burrows occupied by bilbies.

The abundance survey showed that bilbies across the Fitzroy catchment region are found in populations of varying sizes. This information can provide a baseline against which future abundance surveys can be compared, to assess the relative stability of populations. Habitat suitability models confirmed that the majority of suitable bilby habitat occurs in the southern portion of the project area. Based on data from occupancy, density and habitat suitability, the bilby population size within the Fitzroy catchment region was estimated at 11,806 (± 6,068) individuals.

Bilby occupancy across the area, coupled with large areas of potentially suitable habitat, confirm the Fitzroy River catchment as important for the continued persistence of bilby populations, particularly with the continued contraction in range and decreases in occupancy across the nation. Recommended management options that reduce threats and benefit bilby populations are provided.

1. Introduction

As part of the Australian Government's National Environmental Science Program (NESP) Northern Australia Environmental Resources Hub, the Fitzroy River catchment bilby project brings together on-Country Traditional Owner land managers and researchers to build management capacity and help secure the future for bilbies in this area. Coordinated by the Western Australia Department of Biodiversity, Conservation and Attractions (DBCA), along with Environs Kimberley, this project helps to fulfil a primary objective of the Interim Conservation Plan for the Greater Bilby (Bradley et al. 2015): to retain and maintain the naturally occurring distribution and genetic diversity of the bilby through understanding populations at the margin of the species' range; gain information on threats to populations; and identify cost-effective strategies that can be implemented to manage threats.

The Fitzroy River catchment encompasses an area extending inland from Dampier Downs Station in the west to Moola Bulla Station in the east. It covers an expansive area approximately 500 km × 350 km encompassing many different habitat types. Tenure in the Fitzroy River catchment area is mostly pastoral lease. This study encompassed the Fitzroy River catchment with a 50 km buffer, as well as an area to the north-east (on Kija Country) identified as potential bilby habitat, all herein after referred to as the 'project area' (Figure 1.1).

The greater bilby (*Macrotis lagotis*) is a burrowing marsupial that was once widespread (Figure 1.2) across most of mainland Australia (Marlow 1958; Southgate 1990; Friend 1990; Gordon et al. 1990; Johnson and Southgate 1990; Abbott 2001; Bradley et al. 2015). The bilby is now listed as Vulnerable under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (Department of the Environment and Energy 2021); as Vulnerable under the Western Australian *Biodiversity Conservation Act 2016* (Government of Western Australia 2021); and as Vulnerable on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN 2021).

The species has an important ecological role in arid environments as an ecosystem engineer through the beneficial digging, soil turn-over and habitat that bilbies create (James and Eldridge 2007; Read et al. 2008; Newell 2008; James et al. 2011; Fleming et al. 2014; Hofstede and Dziminski 2017), and as an indicator species of environmental conditions (Southgate 1994). The bilby has high cultural (Paltridge 2016; Walsh and Custodians of the Bilby 2016) and iconic (Bradley et al. 2015) significance to Australians. Within the project area, the bilby is very important to Traditional Owners, both culturally through associated creation stories (Martin et al. 2013) and at a management level through the recognition of the species as important for management by Indigenous Ranger groups in Healthy Country Plans (e.g. Yanunijarra Aboriginal Corporation 2012). In the project area the bilby name is:

- Nyarlgoo – Gooniyandi
- Mirtuluju – Walmajarri (Ngurrara)
- Nyalgu – Bunuba
- Mangka-ban – Nyikina
- Jilkarr – Mangala
- Lilgoonel – Kija.

Since European colonisation of Australia, the range and abundance of the bilby (Figure 1.2) has contracted severely (Southgate 1990; Bradley et al. 2015). Since the late 1800s, bilbies have disappeared from at least 80% of their former range (Southgate 1990), and the lesser bilby (*Macrotis leucura*), a closely related species, has become extinct (IUCN 2008).

The decline of bilbies has been attributed to a number of threats working directly or in combination. These threats include predation by introduced cats and foxes (Paltridge 2002; Bradley et al. 2015), changed and inappropriate fire regimes (Southgate and Carthew 2006; Southgate and Carthew 2007; Southgate et al. 2007a; Bradley et al. 2015), and the degradation of bilby habitat through introduced herbivores and land clearing (Southgate 1990; Pavey 2006; Department of Environment 2016).

The current distribution is now restricted to the Tanami Desert, Northern Territory (Johnson and Southgate 1990); the Great Sandy, Little Sandy and Gibson Deserts; parts of the Pilbara and Kimberley in Western Australia (Friend 1990; Dziminski et al. 2018; Dziminski et al. 2020); and an outlying population between Boulia and Birdsville in south-west Queensland (Gordon et al. 1990; McRae 2004). Northern Western Australia, encompassing the west Kimberley, Pilbara and the western deserts, is believed to be a stronghold for extant bilby populations; however, there appears to be an ongoing decline in their range, with a gradual contraction to the north-west (Bradley et al. 2015).

Throughout most of their range, bilbies occur in low densities, show low site fidelity, and are thought to be highly mobile in response to resource availability and habitat modification (Southgate et al. 2007a). This mobility and transient use of habitats means that there is a high level of uncertainty in the detection of bilbies, and thus individuals and colonies are difficult to locate and monitor over time.

Apart from general and targeted survey work to determine bilby presence, there have been few studies of the bilby in the north of Western Australia, especially in the west Kimberley. No coordinated systematic surveys or monitoring of bilby populations have previously occurred in the project area and the status of bilby populations here was unknown. This project consisted of three main components: an occupancy survey of bilbies and introduced animals that pose a threat, an assessment of bilby abundance at selected populations (numbers of animals within populations), and the development of habitat suitability models. Outputs of the project will inform on-ground threat abatement actions to reduce the impacts from key threatening processes on the persistence of the species in this region, and provide context for land management recommendations and environmental impact assessments.

This NESP Northern Australia Environmental Resources Hub project is a partnership between DBCA; Environs Kimberley; and the Gooniyandi Rangers, Bunuba Rangers, Ngurrara Rangers, Nyikina Mangala Rangers and Kija Rangers.

1.1 Aim and objectives

The aim of this project was to increase knowledge of occupancy, abundance and distribution of bilbies in the Fitzroy River catchment area, and to identify on-ground management actions that abate the impacts from key threats. Specific objectives of the project were to:

1. survey the occupancy of bilbies and their recognised threats (i.e. feral predators and introduced herbivores)
2. estimate bilby abundance at selected populations
3. estimate habitat suitability for bilbies across the project area.

The research will provide information on the status of the bilby in the Fitzroy catchment and contribute to species recovery planning and threat abatement programs. Project results will also support evidence-based land use planning and environment impact assessment processes.

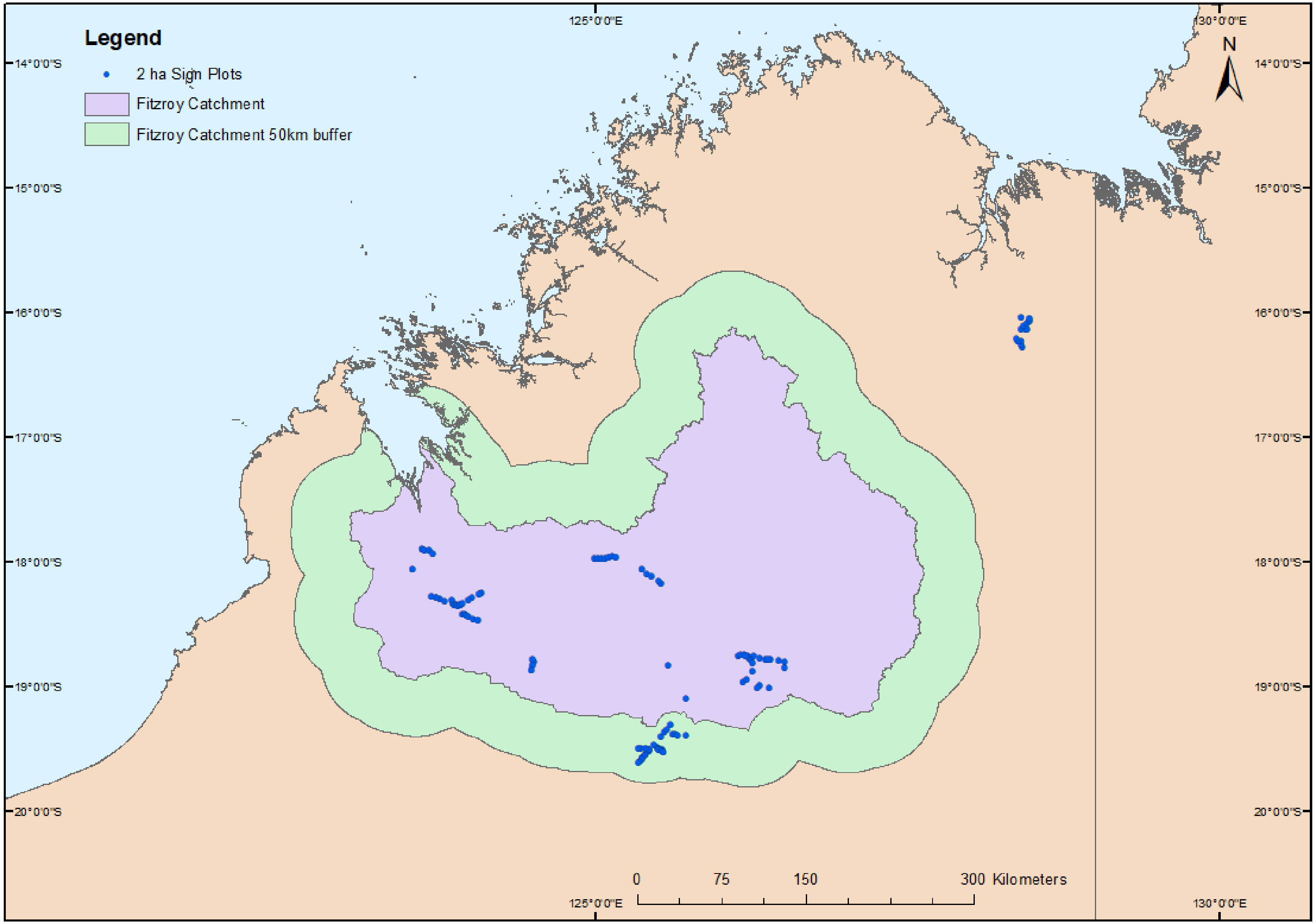

Figure 1.1. The project area.

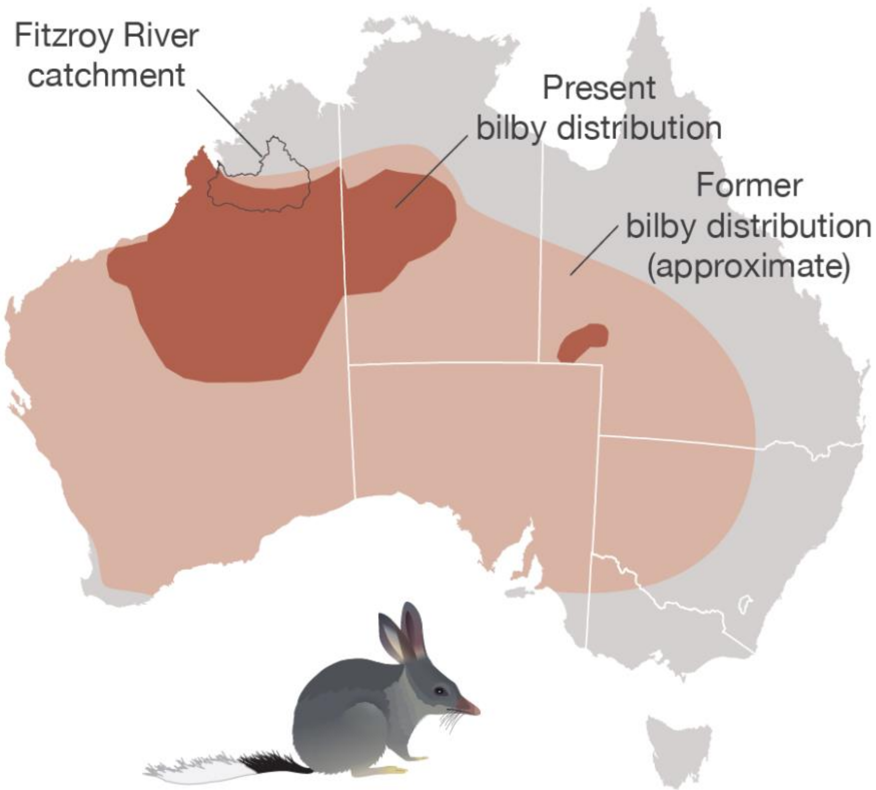

Figure 1.2. Estimated historical and current bilby range.

2. Methods

2.1 Consultation and planning

Consultation with the Prescribed Body Corporate of each Traditional Owner Group, along with the Kimberley Land Council, was undertaken in early 2019 to seek endorsement for the project prior to fee-for-service schedules being developed for each group. Following the execution of project schedules between parties, project staff met with each ranger group to provide information on the project and to undertake planning and training prior to field surveys (Figure 2.1). Training and revision were provided on:

- survey techniques
- identification and verification of animal sign
- identification of key food resources and plants that are important for bilbies
- collection and storage of DNA samples
- digital data capture and management.

Ranger groups were provided with digital devices (tablets) loaded with the required data capture software. Groups were briefed on numbers of plots required to be completed, populations for abundance surveys and project timelines. With guidance from project staff, ranger groups planned and mapped out proposed plot locations based on their knowledge and access to Country and suitable bilby habitat.

Figure 2.1. Planning group meeting with Ngurrara Rangers in Fitzroy Crossing.

2.2 Information sheet

A project information sheet (0) was prepared and distributed to ranger groups and relevant stakeholders such as pastoral lease holders. Subsequent verbal communication with land managers in the project area was undertaken by project staff and/or ranger groups to arrange access.

2.3 Land access

Many of the survey areas within the project area occur on pastoral leases, thereby requiring permission to access. Through liaison and negotiation, access to some leases was provided, although some restrictions required reconsideration of the design and extent of the survey. Unfortunately, access to some pastoral leases was denied, excluding surveys from these areas. Restricted vehicle access to existing tracks also resulted in reduced spatial coverage of sign plot surveys in some areas.

2.4 Occupancy survey

2.4.1 Field survey

Sign plots were distributed in areas of plausible bilby habitat where permission to access was granted, and vehicle access was possible within the project area (Figure 2.2). Plots were spaced more than 3 km apart to ensure independence and increase efficiency by limiting oversampling within the movement range of a single bilby during a survey event. Sign plots were allocated to 109 locations and surveyed on three occasions (0).

The standardised 2 ha sign plot technique provides systematically quantified and comparable data and is currently applied broadly in parts of arid and semi-arid Australia (Moseby et al*.* 2009; Southgate et al*.* 2018). At each 2 ha plot, trained observers recorded animal sign as well as plot covariates in a 2 ha area and within 100 m of nearby vehicle track. During this survey, data was collected electronically using Mobile Data Studio (CreativityCorp Pty Ltd; 0 and 0).

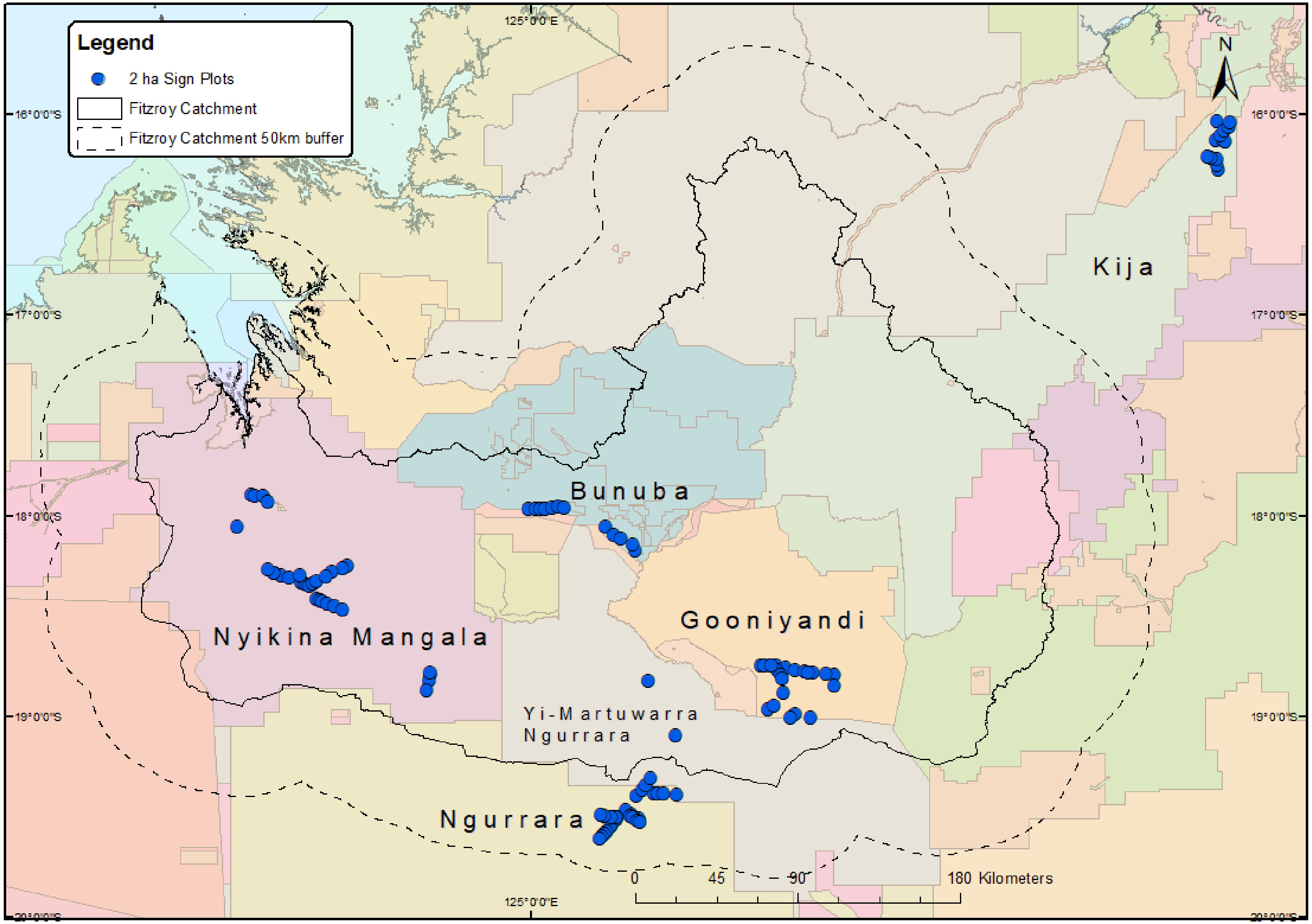

Figure 2.2. Locations of 2 ha sign plots surveyed and used in occupancy analyses.

2.4.2 Occupancy analysis

Occupancy is defined as the probability that a species uses a location (i.e. were recently present in the 2 ha plot, but may not be physically there at the time of surveying), which may depend on various factors (e.g. vegetation type, fire frequency, grazing pressure, predators). It can also be interpreted as the proportion of 2 ha plots used by the species. In the occupancy surveys, detection was defined as the probability of detecting evidence of the focal species given the species uses the 2 ha plot. The detection data were analysed using occupancy models that explicitly account for imperfect detection (MacKenzie et al. 2002), to identify potential factors that may determine where bilbies are more likely to be present. Not accounting for detection probability may lead to misleading inferences about what factors are important for bilby presence (MacKenzie et al. 2006). Occupancy of bilbies and their recognised threats (introduced predators and herbivores) were examined.

Due to the number of covariates of interest, there were potentially a very large number of models that could be fitted to the data, which increases the possibility of obtaining spurious results, that is, identifying combinations of covariates that fit the data well, but provide poor predictions outside of the sample. To mitigate against this, the following approach was used.

For each species, covariates (Table 2.1) were only added to generate candidate models, which were fitted and designed to reflect hypotheses regarding the effects of relevant ecological interactions on occupancy and detection probability. All combinations of these models for occupancy and detection (Table 2.2) were fitted to the data and compared on the basis of Akaike information criterion (AIC) to identify which covariate categories had some explanatory power for each parameter type. Models with convergence issues or error estimating the convergence matrix were removed from the final model set. Across the plots, fire frequency and years since last burnt (NAFI 2021) were strong related ($y=-0.63x+8.05$; $R^2=0.18$, $p<0.001$); therefore, only fire frequency was used.

Tracks of larger animals last longer in the environment; for example, cat or dingo tracks can be detectable for weeks or months in the substrate, and the tracks and scats of very large animals such as cattle and camels last for many months. This produces inflated occupancy values for larger species and confounds comparison of occupancy with smaller animals whose tracks can disappear in hours or days. Therefore, for cats and larger animals, only fresh sign (up to 3 days old) was included in analyses. There were not enough observations of camel sign less than 3 days old, so sign up to 7 days old was used. There were also few feral horse observations, so all sign was included.

Model averaged estimates of occupancy and detection were calculated to account for model selection uncertainty (MacKenzie et al. 2006). All occupancy analyses were conducted in R using the ‘RPresence’ package.

Table 2.1. Description of covariates considered for occupancy and detection probabilities.

Covariate	Description	Code
Vegetation type	Open grassland, shrubland, open woodland or dense woodland	Veg_cov
Cattle grazing pressure	Low (not much sign of cattle), medium (some cattle, but not severely damaged) or high (lots of cattle dung, tracks and damage)	Grazing_cov
Fire frequency	Number of years plot detected as burnt between 2000 and 2020 (NAFI 2021)	Fire_freq
Cat occupancy	Model averaged estimates of the occupancy probability of feral cats	Cat_occupancy
Dingo occupancy	Model averaged estimates of the occupancy probability of dingoes	Dingo_occupancy
Cattle occupancy	Model averaged estimates of the occupancy probability of domestic cattle	Cattle_occupancy
Camel occupancy	Model averaged estimates of the occupancy probability of feral dromedary camels	Camel_occupancy

Table 2.2. Parameters used to generate candidate models.

Occupancy parameters	Detection parameters
Dingo and camel (64 models each)	
psi(Veg_cov)	p(Veg_cov)
psi(Grazing_cov)	p(Grazing_cov)
psi(Fire_freq)	p(Fire_freq)
psi(Grazing_cov+Fire_freq)	p(Grazing_cov+Fire_freq)
psi(Grazing_cov+Veg_cov)	p(Grazing_cov+Veg_cov)
psi(Veg_cov+Fire_freq)	p(Veg_cov+Fire_freq)
psi(Grazing_cov+Fire_freq+Veg_cov)	p(Grazing_cov+Fire_freq+Veg_cov)
psi(.)	p(.)
Feral cat (72 models)	
psi(Veg_cov)	p(Veg_cov)
psi(Grazing_cov)	p(Grazing_cov)
psi(Fire_freq)	p(Fire_freq)
psi(Grazing_cov+Fire_freq)	p(Grazing_cov+Fire_freq)
psi(Grazing_cov+Veg_cov)	p(Grazing_cov+Veg_cov)
psi(Veg_cov+Fire_freq)	p(Veg_cov+Fire_freq)
psi(Grazing_cov+Fire_freq+Veg_cov)	p(Grazing_cov+Fire_freq+Veg_cov)
psi(Dingo_occupancy)	p(.)
psi(.)	
Cattle (16 models)	
psi(Veg_cov)	p(Veg_cov)
psi(Fire_freq)	p(Fire_freq)
psi(Veg_cov+Fire_freq)	p(Veg_cov+Fire_freq)
psi(.)	p(.)

Bilby (136 models)	
psi(Veg_cov)	p(Veg_cov)
psi(Grazing_cov)	p(Grazing_cov)
psi(Fire_freq)	p(Fire_freq)
psi(Cat_occupancy)	p(Cat_occupancy)
psi(Dingo_occupancy)	p(Dingo_occupancy)
psi(Cattle_occupancy)	p(Cattle_occupancy)
psi(Camel_occupancy)	p(Camel_occupancy)
psi(Cat_occupancy+Cattle_occupancy)	p(.)
psi(Dingo_occupancy+Cattle_occupancy)	p(Veg_cov+Fire_freq)
psi(Cat_occupancy+Dingo_occupancy)	
psi(Cat_occupancy+Camel_occupancy)	
psi(Dingo_occupancy+Camel_occupancy)	
psi(Grazing_cov+Fire_freq)	
psi(Grazing_cov+Veg_cov)	
psi(Veg_cov+Fire_freq)	
psi(Grazing_cov+Fire_freq+Veg_cov)	
psi(.)	

2.5 Predator occupancy at bilby populations

Vehicle tracks provide movement corridors for invasive predators and activity of predators on tracks can be magnitudes higher than off tracks (Raiter et al. 2018). Since the main objective of this part of the study was to survey feral predators, we positioned cameras observing vehicle tracks to increase the detection of these target species. Bilby burrows can also act as natural lures in the landscape, with many other prey species, as well as bilbies, inhabiting them, attracting predators that regularly visit these features in an often barren landscape (Hofstede and Dziminski 2017; Dawson et al. 2019). Therefore, we also positioned cameras on bilby burrows to increase detection of feral predators. As dingoes are known to prey on bilbies, observations of dingoes were also included in analyses.

2.5.1 Remote cameras

Remote cameras (Reconyx Hyperfire 2, Reconyx, Wisconsin; USA) were allocated to six locations at the three bilby populations that were surveyed for abundance. At each population, three cameras were positioned observing vehicle tracks, and three were positioned observing bilby burrow entrances. Cameras were positioned approximately 2 km apart, or as far apart as possible on burrows. Cameras were deployed at Yarri Yarri (Nyikina Mangala) from 14 September to 28 October 2020, Kurlku (Ngurrara) from 8 October to 24 November 2020 and Bawoorrooga (Gooniyandi) from 2 October to 7 December 2020.

Camera settings are given in 0. Cameras were attached to 1.8 m steel fencing posts using a 'Direct Mount' (Outdoor Cameras Australia; Figure 2.3). At the Bawoorrooga (Gooniyandi) population, three extra fencing posts were added around the central camera post as a barrier to prevent cattle interfering with cameras.

2.5.2 Image analyses

Colorado Parks and Wildlife Photo Warehouse was used to store and score images, and to generate occupancy data (binary presence/absence) for occasions of 7-day periods.

2.5.3 Occupancy analyses

Candidate models included simple, single-season models with no covariates [*psi(.)p(.)*], and models with covariates reflecting differing detections due to camera placement on burrows or tracks [*psi(.)p(On tracks)*]. Confidence intervals (5–95%) and beta values were calculated. High beta values signify that the associated occupancy or detection value should be interpreted with caution, usually because of a low or insufficient number of observations. When occupancy or detection is or approaches 1 or 0, the associated beta values can also be inflated. When occupancy or detection values approach 1, they also become unreliable for interpretation. If a model is more than two AIC units lower than another (ΔAIC), then it is considered significantly better than the other model. Since all occasions were within the same season, we expected no survey-time-specific effects on detection.

Figure 2.3. Setting up a remote camera at the Kurlku (Ngurrara) bilby population.

2.6 Bilby abundance surveys

Abundance surveys were undertaken following the procedures described in Dziminski et al. (2021) and detailed below.

2.6.1 Determining the extent of the population

Abundance surveys were undertaken at three populations identified and selected during the initial phases of the occupancy survey. The populations were selected based on geographic representation in the project area, access, and time constraints. The populations were located on Nyikina Mangala Country, Gooniyandi Country and Ngurrara Country (Figure 2.4).

The extent of populations was mapped using vehicles and on foot, depending on vegetation and terrain (Figure 2.5). Global positioning system coordinates of the extent of bilby activity were plotted on electronic devices, and where no more sign of activity (tracks, scats, diggings, burrows) existed, the population boundary was delineated. This process was completed typically in 1–3 days, then transects to be traversed were overlaid to ensure the population was evenly sampled. We used the population extent as the ‘habitat mask’ in spatially explicit capture-recapture (SECR) analyses (see Section 2.6.4).

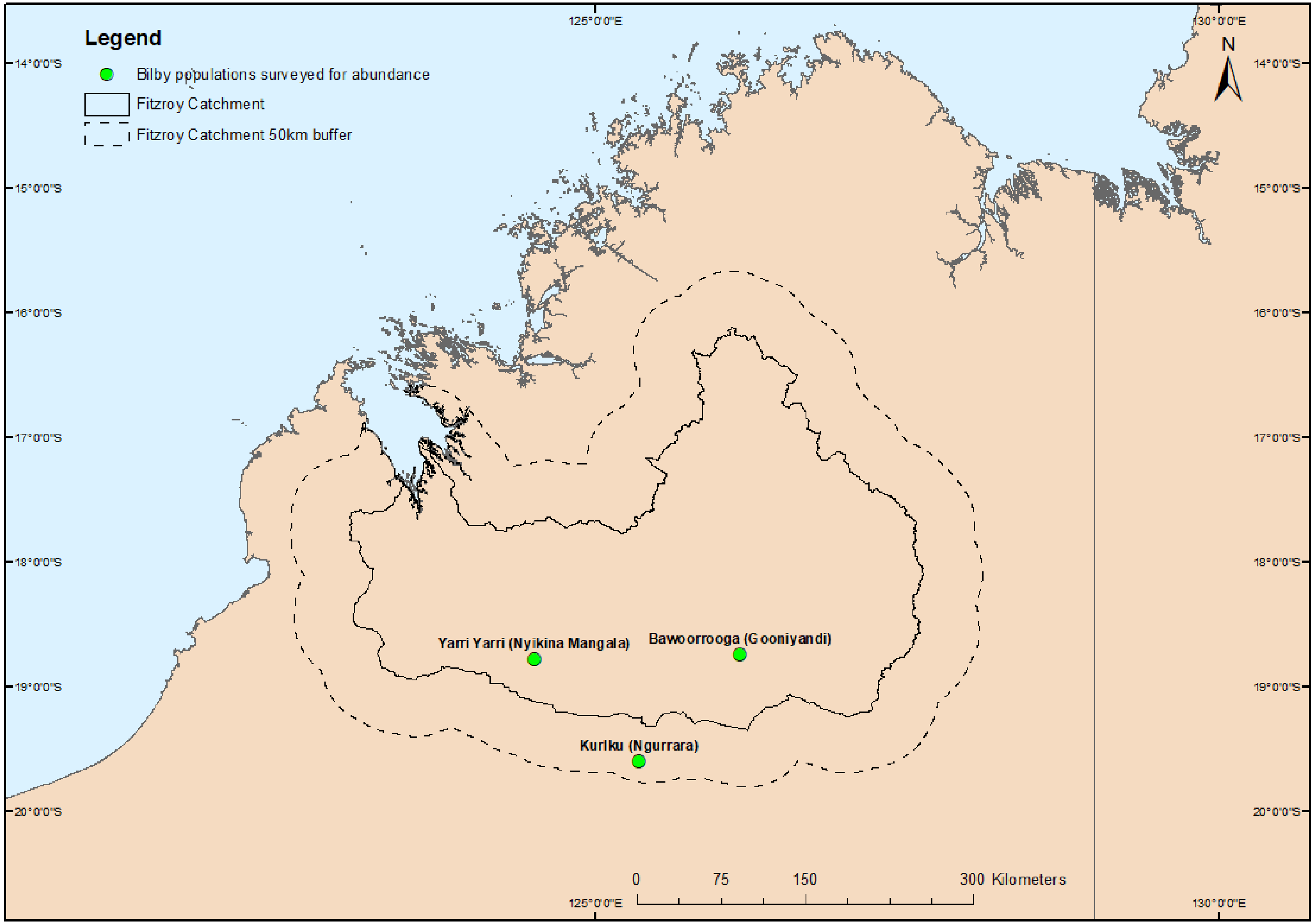

Figure 2.4. Locations of populations where abundance surveys were undertaken.

Figure 2.5. Mapping the bilby activity area at the Kurlku (Ngurrara) bilby population.

2.6.2 Sample collection

Transects were positioned to sample population extents, ensuring access to start or end points from roads or tracks where available. We ensured transects crossed the majority of the population extent, within the constraints of access depending on terrain. Larger activity areas required longer transects to ensure coverage. Transects were traversed on foot to collect bilby scats. Each transect was sampled once. Individual bilbies deposit single or a small number of faecal pellets (usually 2–5) in a discrete group, usually on top of or within the sand-spoil of food diggings (Figure 2.6). Bilby scats are difficult to age just by visual inspection.

Clearly decomposed or broken up scats were not collected. The age of these scats was able to be assessed by examining the state of decomposition of the associated digging. If the digging was eroded and weathered, indicating it was created probably >2 weeks prior, then the associated scats were not collected because the scats were less likely to yield DNA (Carpenter and Dziminski 2017). Collected scats were placed in labelled 30 mL plastic tubes, approximately 33% filled with silica gel beads and a cotton wool ball, until DNA extraction. The silica gel ensured pellets remained dry because moisture degrades DNA. The cotton ball reduced rubbing of beads against pellets, which may remove bilby epithelial cells from the surface of the pellet, reducing available cells for DNA extraction.

Pellets in a group, in contact with or very close to each other, were considered to be from one individual and were stored in a single vial. Pellets were scooped from the ground into the vial using the lid or a small stick (Figure 2.7), used only for the one sample to avoid cross-contamination. Vials with samples were transported in a cooler bag, kept out of the sun and stored at room temperature until DNA extraction.

Figure 2.6. An example of a bilby digging with scats collected for population abundance analysis.

Figure 2.7. Collection of DNA samples for the abundance survey.

2.6.3 DNA extraction, PCR amplification and genotyping

Extractions were completed using the Omega Bio-tek Mag-Bind® Stool DNA 96 Kit (Omega Bio-tek, Norcross, GA, USA) with two main modifications to the the manufacturer's protocol: the required 300 µL stool sample was produced by adding 800 µL of stool lysis buffer (see Deuter et al*.* 1995 for SLP buffer) to a surface scraping of the faecal pellet; and samples were left to air dry overnight prior to a single 100 µL elution. DNA samples were stored at −20°C until amplified using PCR.

PCR amplification was undertaken using eight bilby-specific polymorphic microsatellite markers (Moritz *et al.* 1997; Smith *et al.* 2009) amplified across two multiplexes with fluorescent-labelled markers from the G5 filter set: multiplex 1 (B02 [6FAM], B17 [VIC], B56 [PET] and B66 [NED]) and multiplex 2 (B55 [6FAM], B22 [VIC], B41 [PET] and B63 [NED]). PCRs were run as described in Carpenter and Dziminski (2017) with 2–4 µL of DNA used in a 12.5 µL reaction for each replicate. A minimum of two PCRs were performed for each scat sample. Where these two samples provided a consensus result, further PCRs were not completed. For samples where alleles were not clear or were inconsistent, a third PCR was run to confirm the genotype of the individual. Where genotyping across all loci was not achieved from the initial PCRs, no further PCRs were undertaken for that sample, and the sample was eliminated from the dataset.

Plates containing PCR products were stored at −20°C until fragment analysis. PCR products were analysed on an ABI3730XL Sequencer and fragments sized using the GeneScan 500 LIZ size standard (Applied Biosystems, Waltham, MA, USA). Alleles were scored using GeneMapper version 5 (Applied Biosystems). Results were reviewed manually to ensure consistent scoring of alleles and to confirm any genotyping errors such as the presence of false alleles (Bonin et al*.* 2004; Broquet and Petit 2004; Waits and Paetkau 2005) and allelic dropouts (Broquet and Petit 2004). An allele was considered to be a true allele when it was replicated at least twice across three PCRs.

Allele matching was completed using the R package 'AlleleMatch' (Galpern et al*.* 2012). Unclassified samples were examined manually and samples that matched multiple unique genotypes were excluded if they could not be matched or classified as new unique genotypes. Any remaining mismatched alleles were flagged and examined to determine genotyping errors. Genotypes identified along transects only provide information on the number of individuals detected specifically on transects, which requires further analysis to calculate the number of individuals within the extent of the population.

2.6.4 Abundance analyses

SECR analyses (SECR: Efford 2004) were used to estimate densities and numbers of animals within the areas of activity. Maximum likelihood SECR analyses were undertaken using the R package 'secr'. Spatial analyses were completed using ArcGIS (Esri, Redlands, CA, USA) and QGIS open source software (Version 3.22.1, www.qgis.org).

Habitat masks were constructed for each population by generating the integration mesh using a buffer around the transects of 4×σ (σ = spatial scale parameter: Efford 2019a; Efford 2019b) and clipping with the population extent polygons for wild populations (area outside the population extent excluded). All samples at each monitoring event were grouped into a single sampling session and occasion.

Transect detectors, the hazard exponential detection function and the Nelder-Mead maximisation algorithm were used. Models using these parameters performed reliably and consistently.

2.7 Habitat suitability models

2.7.1 Maxent

Maximum entropy modelling is a machine-learning process that estimates a probability distribution (Phillips et al*.* 2004; Phillips et al*.* 2006; Yackulic et al*.* 2013). The software package Maxent (Phillips et al*.* 2021) was used to undertake modelling as it is efficient, widely used in applied ecological studies by government agencies and research organisations, and has been shown to perform well in comparison to several other models when there are relatively few presence records available (Elith and Leathwick 2009; Porfirio et al*.* 2014). Although there is much debate on the outputs of Maxent and whether it is interpreted as relative occurrence rate or occupancy probability depending on satisfying underlying assumptions (eg Merow et al*.* 2013; Yackulic et al*.* 2013), for this study we simply interpret Maxent's predictions as indices of habitat suitability (Merow et al*.* 2013).

2.7.2 Bilby presence data

The area modelled was the Fitzroy River catchment with a 50 km buffer (Figure 2.8). Bilby presence data from the occupancy and abundance surveys from this study, nearby similar bilby surveys that overlapped the project area (Dziminski et al*.* 2018; Dziminski and Greatwich 2019), and data from NatureMap (NatureMap 2021) were included. Only records from the year 2000 onwards were included since data on fire frequency is only available from 2000 (see Section 2.7.3). NatureMap data were manually screened and records with uncertainty or without accurate coordinates were excluded. A total of 1,245 bilby presence points were used (Figure 2.8).

2.7.3 Variable selection

To avoid model overfitting, minimise multicollinearity and increase efficiency, the number of variables recommended is ≤10 (Elith and Leathwick 2009; Hijmans 2012). An initial suite of available variables was assessed and those that did not have biological relevance were excluded. Potential ecological variables are shown in Table 2.3.

To reduce the number of potentially useful variables, correlations were examined and a single variable from correlated variables was selected based on ecological relevance. Relationships between continuous variables were examined using Pearson and Spearman rank order correlations and between categorical variables using Pearson χ^2 tests. All variable data layers were converted to a pixel resolution of 0.001 decimal degrees using the WGS 84 datum and clipped to the project area (Fitzroy River catchment with a 50 km buffer) polygon. The vegetation type data layer (NVIS 2021) was used to identify polygons of areas of mangroves, coastal mudflat, human cleared areas (e.g. airfields, mine pits, built-up areas), and fresh and salt lakes and lagoons. As these areas are not potential bilby habitat, they were excluded from all layers used in analyses.

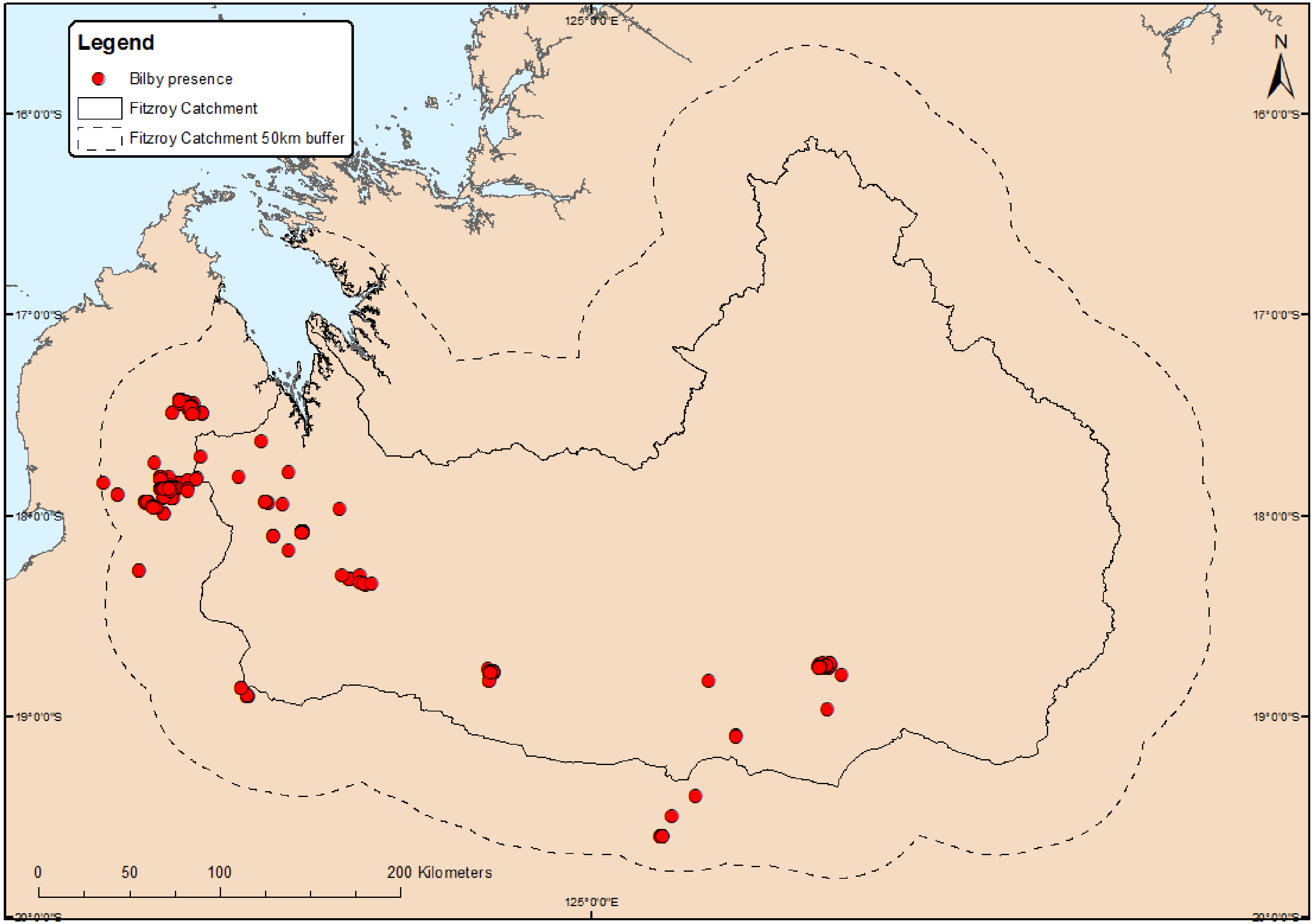

Figure 2.8. Bilby presence records used for Maxent modelling.

2.7.4 Bias compensation

To compensate for survey bias (Kramer-Schadt et al. 2013; Fithian et al. 2015), a bias grid (Figure 2.9) was generated using locations of plots from the occupancy survey from this study, nearby similar bilby surveys that overlapped the project area (Dziminski et al. 2018; Dziminski and Greatwich 2019), and locations where surveys have been conducted by consultants for mining and resources developments (e.g. Thunderbird, Yullaroo, Finders Shale; NatureMap 2021). Sign plot locations were used in the Kernel Density function in ArcGIS 10.1 to construct the grid.

2.7.5 Model parameters

Maxent version 3.4.4 (Phillips et al. 2021) was used to perform 15 replicate runs with a random seed and 25% of the data withheld for testing by subsampling. The remaining model parameters were: iterations=5000, convergence threshold=0.00001, regularisation value=1 and a logistic output format. Results are presented as an index of habitat suitability. Because there were few categorical variables relevant to the project area, and they are coarse and at a very large scale in comparison to the other variables, the Maxent model was rerun excluding any categorical variables that may have an inflated effect on the resulting index of habitat suitability.

Table 2.3. Available variables assessed for Maxent modelling.

Variable	Description	Type	Source
Available water capacity	% at 1–2 m	Continuous	(CSIRO 2021)
BioClim18	Precipitation of warmest quarter	Continuous	(WorldClim 2021)
BioClim19	Precipitation of coldest quarter	Continuous	(WorldClim 2021)
Coarse fragments	Mass fraction of the soil material >2 mm % at 1–2 m	Continuous	(CSIRO 2021)
Clay	<2 µm mass fraction of the <2 mm soil material % at 1–2 m	Continuous	(CSIRO 2021)
Depth of regolith	Depth to hard rock. Depth is inclusive of all regolith (m)	Continuous	(CSIRO 2021)
Depth of soil	Depth of soil profile (A & B horizons) (m)	Continuous	(CSIRO 2021)
Elevation	5 m digital elevation model	Continuous	(ELVIS 2021)
Fire frequency	Number of fires 2000–2017	Continuous	(NAFI 2021)
Prescott index	Measure of water balance that is sensitive to regional climate and local topography	Continuous	(CSIRO 2021)
Relief 300 m radius	Full range of elevations within a 300 m circular radius	Continuous	(CSIRO 2021)
Silt	2–20 µm mass fraction of the <2 mm soil material % at 1–2 m	Continuous	(CSIRO 2021)
Sand	20 µm – 2 mm mass fraction of the <2 mm soil material % at 1–2 m	Continuous	(CSIRO 2021)
Topographic wetness index	Relative wetness within moist catchments, but is more commonly used as a measure of position on the slope with larger values indicating a lower slope position	Continuous	(CSIRO 2021)
Geology	Surface Geology of Australia 1:1,000,000 scale	Categorical	(Geoscience Australia 2021)
Soil type	Digital Atlas of Australian Soils 1:2,000,000 scale	Categorical	(ASRIS 2021)
Vegetation type	National Vegetation Information System Present (Extant) Vegetation 1:250,000 scale	Categorical	(NVIS 2021)

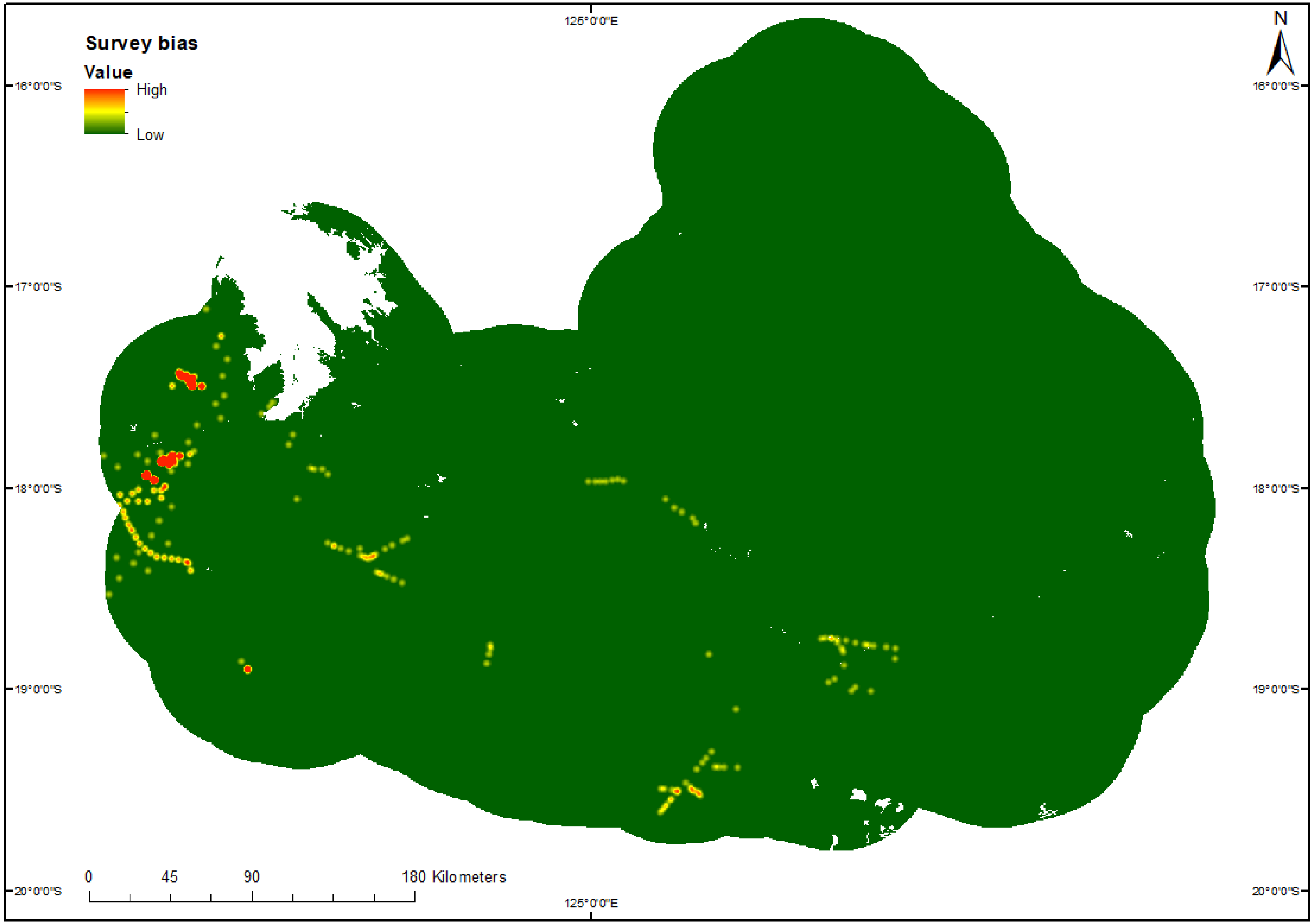

Figure 2.9. Survey bias grid used in Maxent modelling.

2.8 Bilby population estimate for the project area

To estimate the bilby population size of the entire project area (μ), the following equation was used:

$$\mu = Area \times \psi \times \rho$$

where: *Area* = the area (ha) of habitat with a suitability score >0.5 calculated from the highest-ranked habitat suitability model, selected by area under curve (AUC) derived from maximum entropy modelling; ψ = the mean model averaged probability of occupancy of bilbies derived from occupancy analyses; and ρ = mean density of individuals (ha^{-1}) derived from SECR analyses of the three surveyed bilby populations.

3. Results

3.1 Occupancy survey

A list of animals that were recorded from the 109 × 2 ha sign plots across the project area during occupancy surveys is shown in Table 3.1.

Table 3.1. Animals detected from from all-aged sign on 2 ha plots.

Animal	Number of plots detected	Total detections on all occasions
Bilby predators		
Feral cat	79	144
Fox	1	1
Dingo	35	41
Introduced herbivores		
Domestic cattle	81	206
Dromedary camel	48	113
Feral horse	8	8
Mammals		
Agile wallaby	1	1
Brush-tailed mulgara	1	1
Echidna	1	1
Greater bilby	18	29
Red kangaroo or euro	75	108
Mouse/small rodent/dunnart	19	22
Spectacled hare-wallaby	2	2
Spinifex hopping mouse	46	85
Wallaby – unknown	37	43
Reptiles		
Centralian blue-tongued skink	23	28
Lizard – medium	20	20
Lizard – small	87	178
Sand slider (*Lerista*)	53	95
Snake – python	3	3
Snake – unknown	36	51
Varanid lizard – large	25	29
Varanid lizard – small	80	175
Birds		
Australian bustard	56	102
Bird – hopping	11	11
Bird – walking	30	39
Brolga	2	2
Bush stone-curlew	2	2
Emu	9	10
Quail	30	40

3.1.1 Bilby

A total of 29 detections of bilby sign were observed at 18 unique plots. Bilby sign that was recorded included tracks, diggings, diggings into roots for root-dwelling larvae, scats and burrows (Figure 3.1).

Based on the estimated occupancy and detection probabilities from the simplest model, with no covariates on either component, bilby occupancy was estimated at 0.20 (± 0.05 standard error [SE]) with a per survey detection probability of 0.45 (± 0.09 SE). The mean model averaged occupancy using the top five models was estimated at 0.21 (± 0.07 SE) and the per survey detection probability at 0.49 (± 0.14 SE).

Figure 3.1. Typical active bilby tracks and burrow recorded during field surveys.

The five highest-ranked models from model fitting are shown in Table 3.2. Model averaged estimates of the occupancy probability at each plot are mapped in Figure 3.2, with associated standard errors presented in Figure 3.3. The results of the model fitting indicate that cattle occupancy influenced bilby occupancy and that a combination of vegetation type and fire frequency best described the detection of bilby at occupied plots.

Bilby occupancy probability was estimated to decline with increasing cattle occupancy (Figure 3.4). Bilby detection probability was estimated to be highest in open woodland (Figure 3.5) and tended to increase with fire frequency (Figure 3.6), although the relationship was uncertain as indicated by the large size of the confidence interval. It may be that detectability is higher in the more open habitat type that also tended to have a higher fire frequency (Figure 3.7).

Table 3.2. Summary of the five highest-ranked models compared using Akaike information criterion (AIC) for bilby occupancy and detection.

Model number	Model	AIC	ΔAIC	Negative 2 loglikelihood	Number of parameters	Weight
41	psi(Cattle_occupancy)p(Veg_cov)	165.4628	0	157.4628	4	0.0667
48	psi(Cattle_occupancy)p(.)	165.9293	0.4665	159.9293	3	0.0528
46	psi(Cattle_occupancy)p(Veg_cov+Fire_freq)	166.7310	1.2682	156.7310	5	0.0354
57	psi(Cat_occupancy+Cattle_occupancy)p(Veg_cov)	166.9101	1.4473	156.9101	5	0.0323
43	psi(Cattle_occupancy)p(Fire_freq)	167.1990	1.7362	159.1990	4	0.0280

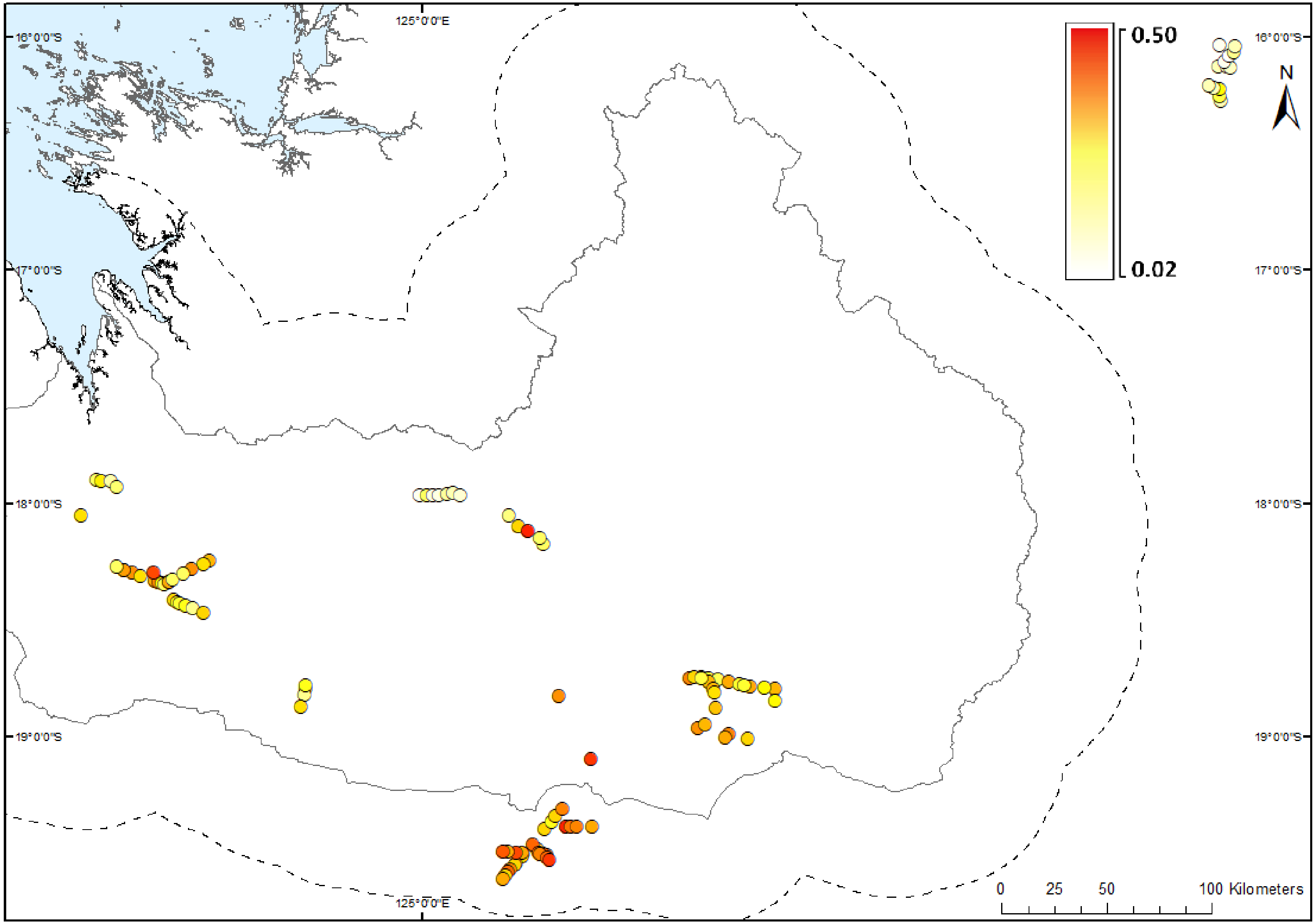

Figure 3.2. Model averaged estimate for probability of bilby presence at each surveyed plot.

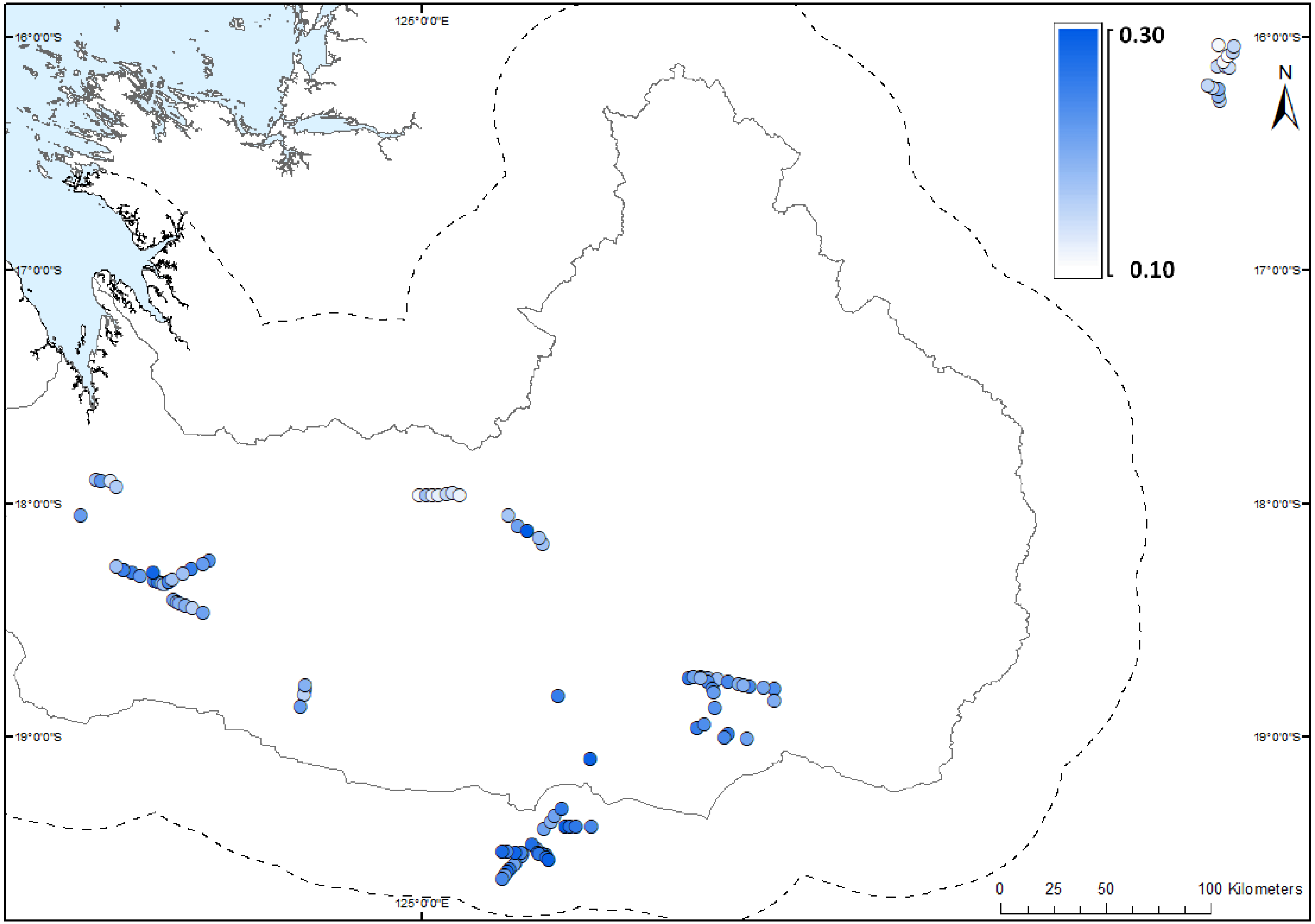

Figure 3.3. Standard error of model averaged estimate for probability of bilby presence at each surveyed plot.

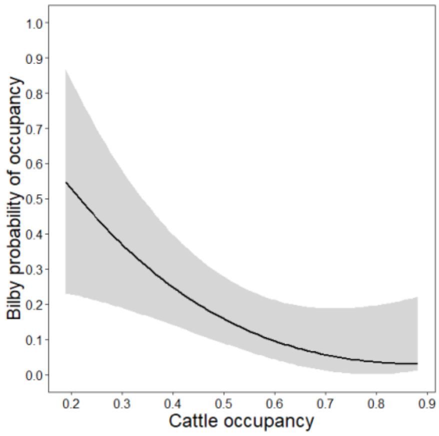

Figure 3.4. Model averaged bilby occupancy probability and 95% confidence interval, as a function of cattle occupancy.

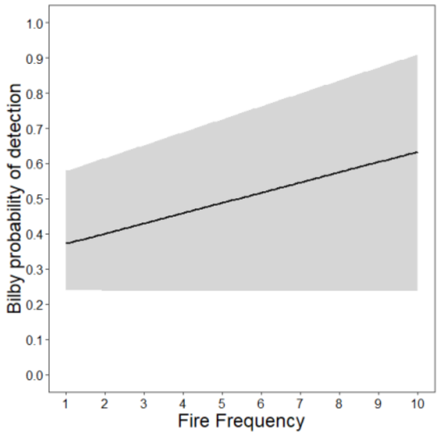

Figure 3.6. Model averaged bilby detection probability and 95% confidence interval, as a function of fire frequency.

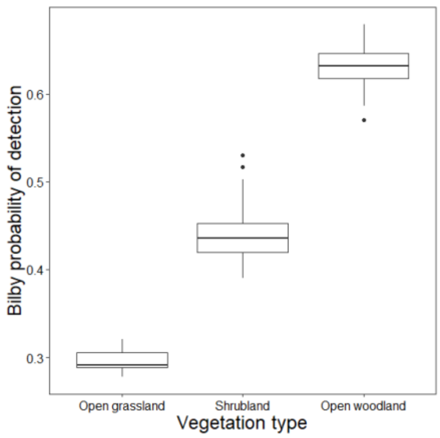

Figure 3.5. Model averaged bilby detection probability as a function of vegetation type.

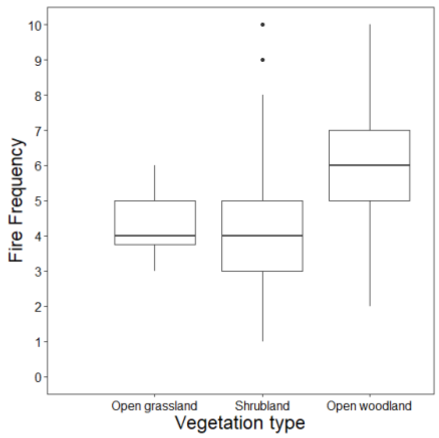

Figure 3.7. Fire frequency within the observed vegetation types.

3.1.2 Feral cat

A total of 70 detections of feral cat (*Felis catus*) sign were observed at 54 unique plots.

Based on the estimated occupancy and detection probabilities from the simplest model, cat occupancy was estimated at 0.86 (± 0.15 SE) with a per survey detection probability of 0.25 (± 0.05 SE). The mean model averaged occupancy using the top five models was estimated at 0.91 (± 0.14 SE) and the per survey detection probability at 0.24 (± 0.06 SE).

The five highest-ranked models from model fitting are shown in Table 3.3. Model averaged estimates of the occupancy probability at each plot are mapped in Figure 3.8, with associated standard errors presented in Figure 3.9. The results of the model fitting indicate that dingo occupancy and vegetation type influenced cat occupancy and that a combination of cattle grazing pressure, vegetation type and fire frequency best described the detection of cats at occupied plots.

Cat occupancy probability was estimated to decline with increasing dingo occupancy (Figure 3.10) and was highest in shrubland (Figure 3.11). Cat detection probability was estimated to decrease with increasing cattle grazing pressure (Figure 3.12), was highest in shrubland (Figure 3.13) and tended to decrease with increasing fire frequency (Figure 3.14).

Table 3.3. Summary of the five highest-ranked models compared using Akaike information criterion (AIC) for cat occupancy and detection.

Model number	Model	AIC	ΔAIC	Negative 2 loglikelihood	Number of parameters	Weight
61	psi(Dingo_occupancy)p(Grazing_cov+Veg_cov)	335.9029	0.1039	325.9029	5	0.1442
69	psi(.)p(Grazing_cov+Veg_cov)	336.1880	0.3890	328.1880	4	0.1250
2	psi(Veg_cov)p(Grazing_cov)	337.5211	1.7221	329.5211	4	0.0642
63	psi(Dingo_occupancy)p(Grazing_cov+Fire_freq+ Veg_cov)	337.5884	1.7894	325.5884	6	0.0621
66	psi(.)p(Grazing_cov)	337.6922	1.8932	331.6922	3	0.0590

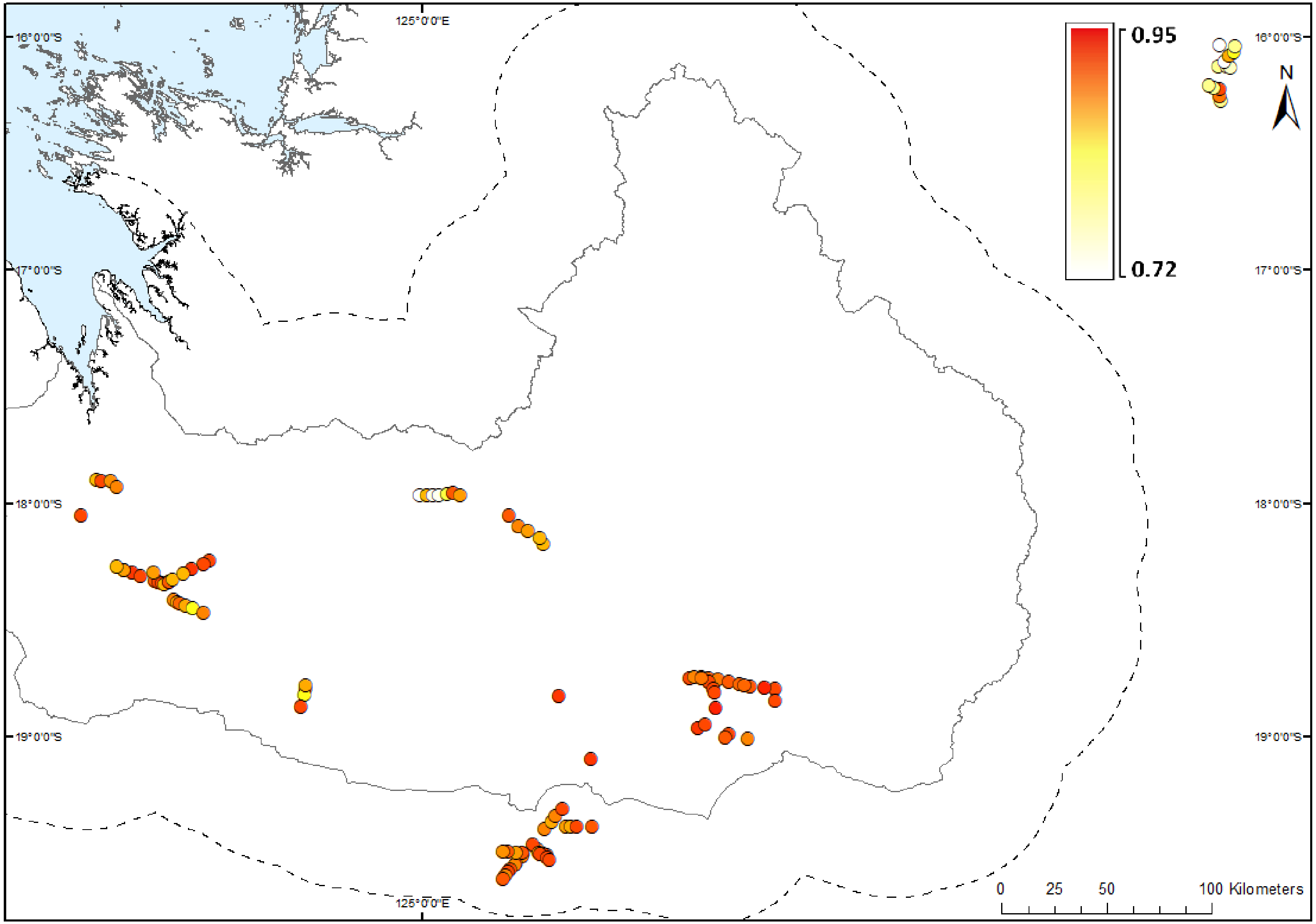

Figure 3.8. Model averaged estimate for probability of cat presence at each surveyed plot.

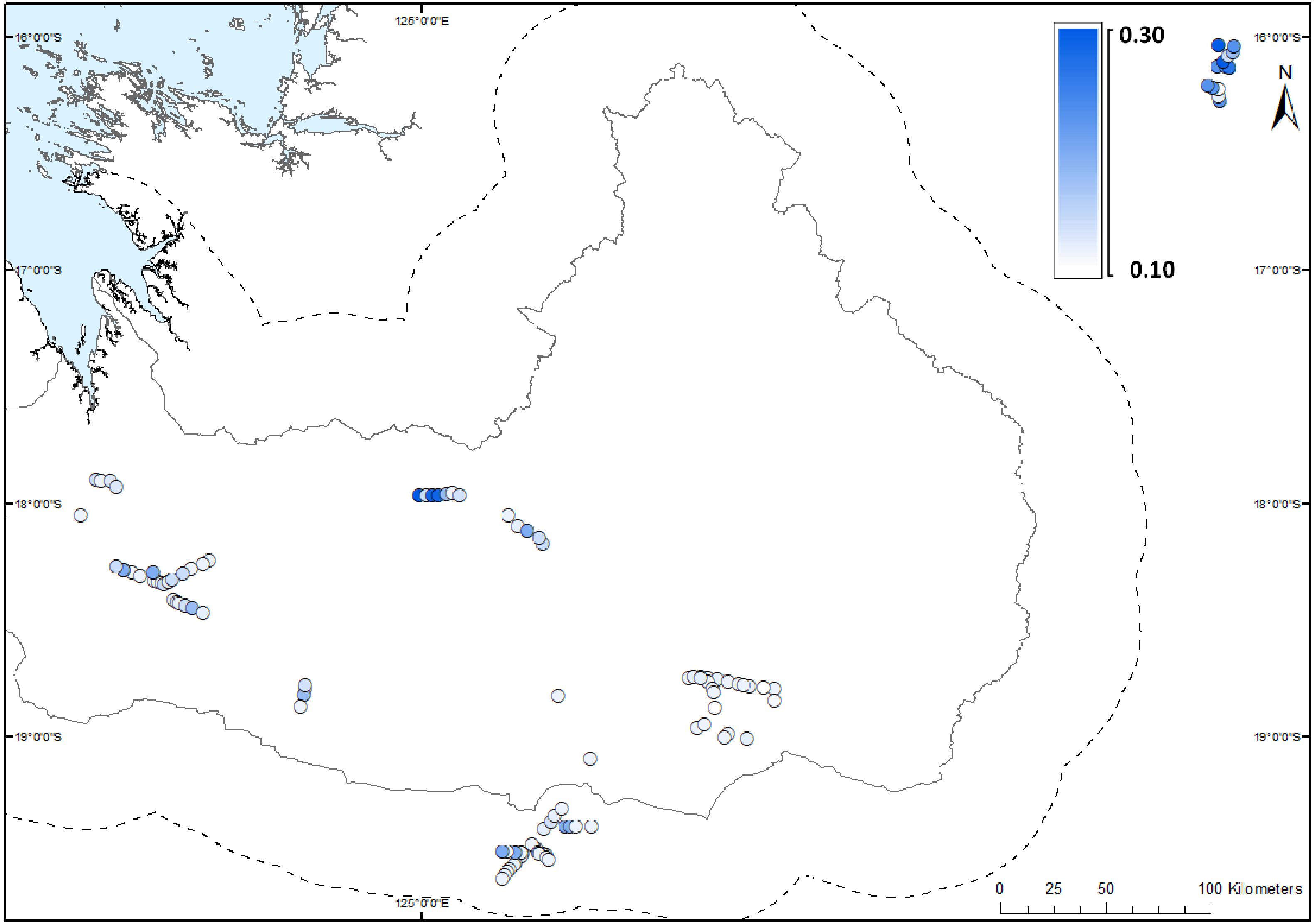

Figure 3.9. Standard error of model averaged estimate for probability of cat presence at each surveyed plot.

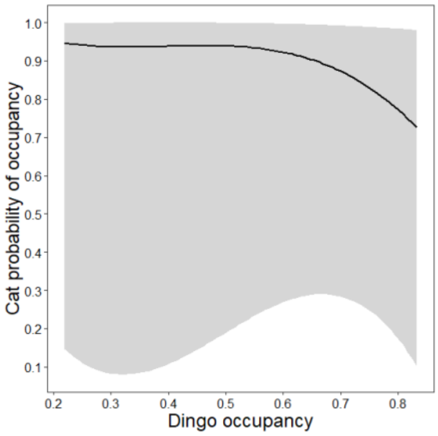

Figure 3.10. Model averaged cat occupancy probability and 95% confidence interval, as a function of dingo occupancy.

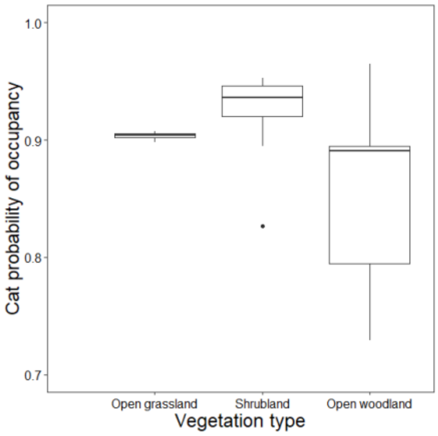

Figure 3.11. Model averaged cat occupancy probability as a function of vegetation type.

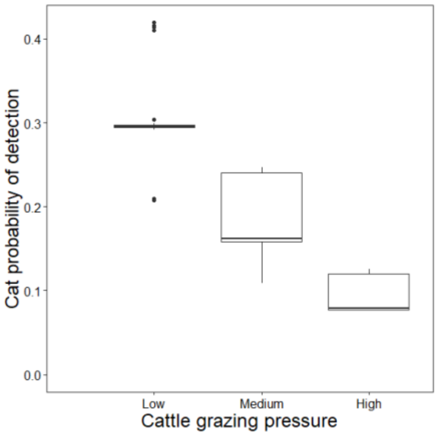

Figure 3.12. Model averaged cat detection probability as a function of cattle grazing pressure.

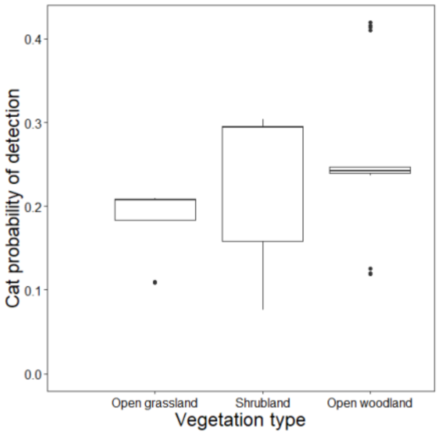

Figure 3.13. Model averaged cat detection probability as a function of vegetation type.

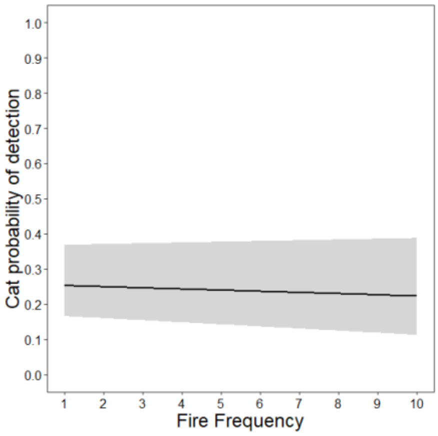

Figure 3.14. Model averaged cat detection probability and 95% confidence interval, as a function of fire frequency.

3.1.3 Dingo

A total of 17 detections of dingo (*Canis lupus dingo*) sign were observed at 15 unique plots.

Based on the estimated occupancy and detection probabilities from the simplest model, dingo occupancy was estimated at 0.42 (± 0.26 SE) with a per survey detection probability of 0.12 (± 0.08 SE). The mean model averaged occupancy using the top five models was estimated at 0.56 (± 0.34 SE) and the per survey detection probability at 0.12 (± 0.09 SE).

The five highest-ranked models from model fitting are shown in Table 3.4. Model averaged estimates of the occupancy probability at each plot are mapped in Figure 3.15, with associated standard errors presented in Figure 3.16. The results of the model fitting indicate that vegetation, fire frequency and a combination of vegetation type and cattle grazing pressure influenced dingo occupancy and that a combination of cattle grazing pressure, vegetation type and fire frequency best described the detection of dingoes at occupied plots.

Dingo occupancy probability was estimated to be highest in open woodland and lowest in open grassland (Figure 3.17), was lower under high cattle grazing pressure (Figure 3.18), and tended to increase with fire frequency, but with high uncertainty (Figure 3.19). Dingo detection probability was estimated to increase with higher cattle grazing pressure (Figure 3.20) and fire frequency (Figure 3.21), and was highest in open woodland and lowest in open grassland (Figure 3.22).

Table 3.4. Summary of the five highest-ranked models compared using Akaike information criterion (AIC) for dingo occupancy and detection.

Model number	Model	AIC	ΔAIC	Negative 2 loglikelihood	Number of parameters	Weight
8	psi(Veg_cov)p(.)	133.1401	0	127.1401	3	0.0595
36	psi(Grazing_cov+Veg_cov)p(Grazing_cov+Fire_freq)	133.3601	0.2200	121.3601	6	0.0533
57	psi(.)p(Veg_cov)	133.3623	0.2222	127.3623	3	0.0532
23	psi(Fire_freq)p(Grazing_cov+Fire_freq+Veg_cov)	133.4374	0.2973	121.4374	6	0.0513
22	psi(Fire_freq)p(Veg_cov+Fire_freq)	133.8645	0.7244	123.8645	5	0.0414

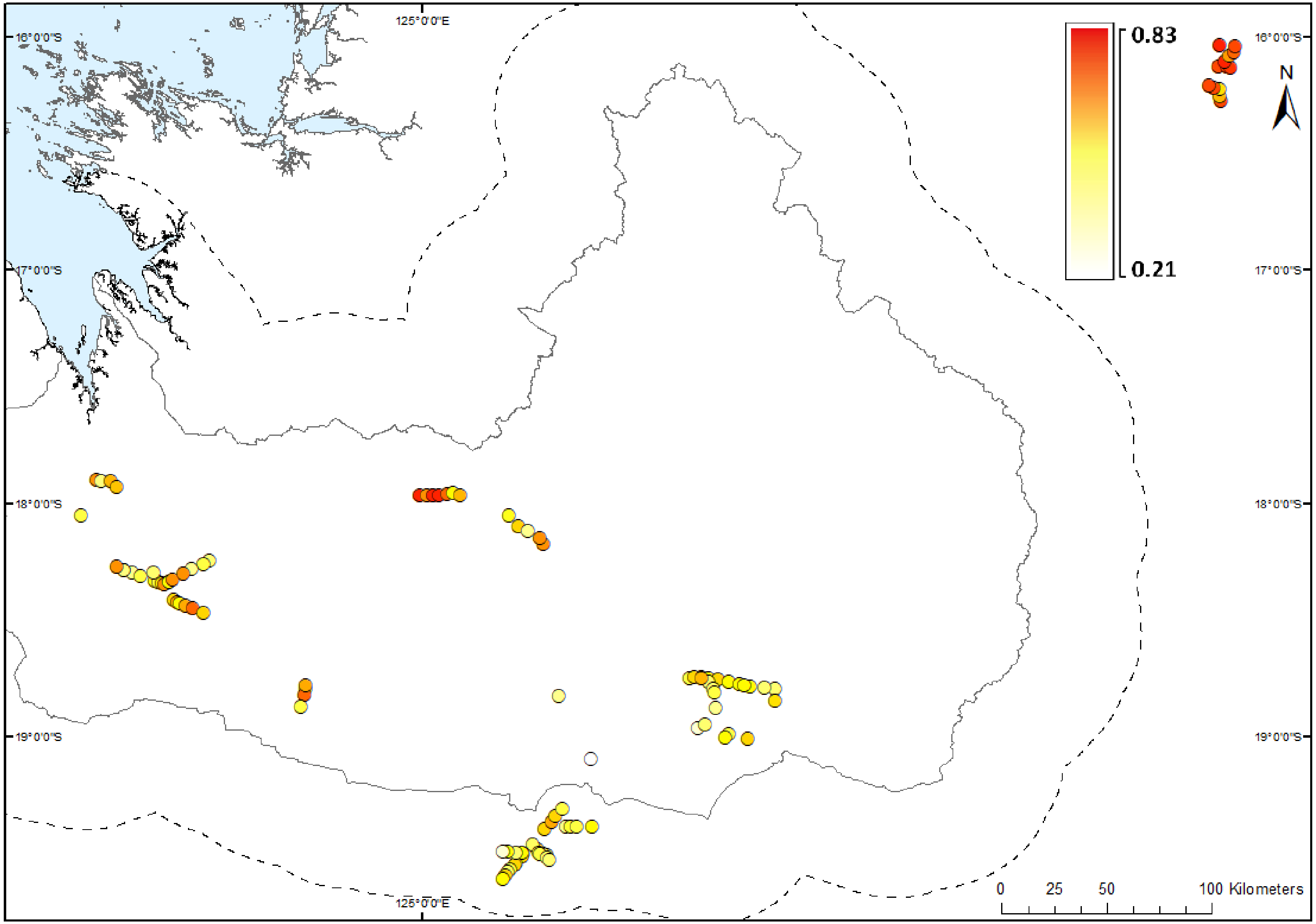

Figure 3.15. Model averaged estimate for probability of dingo presence at each surveyed plot.

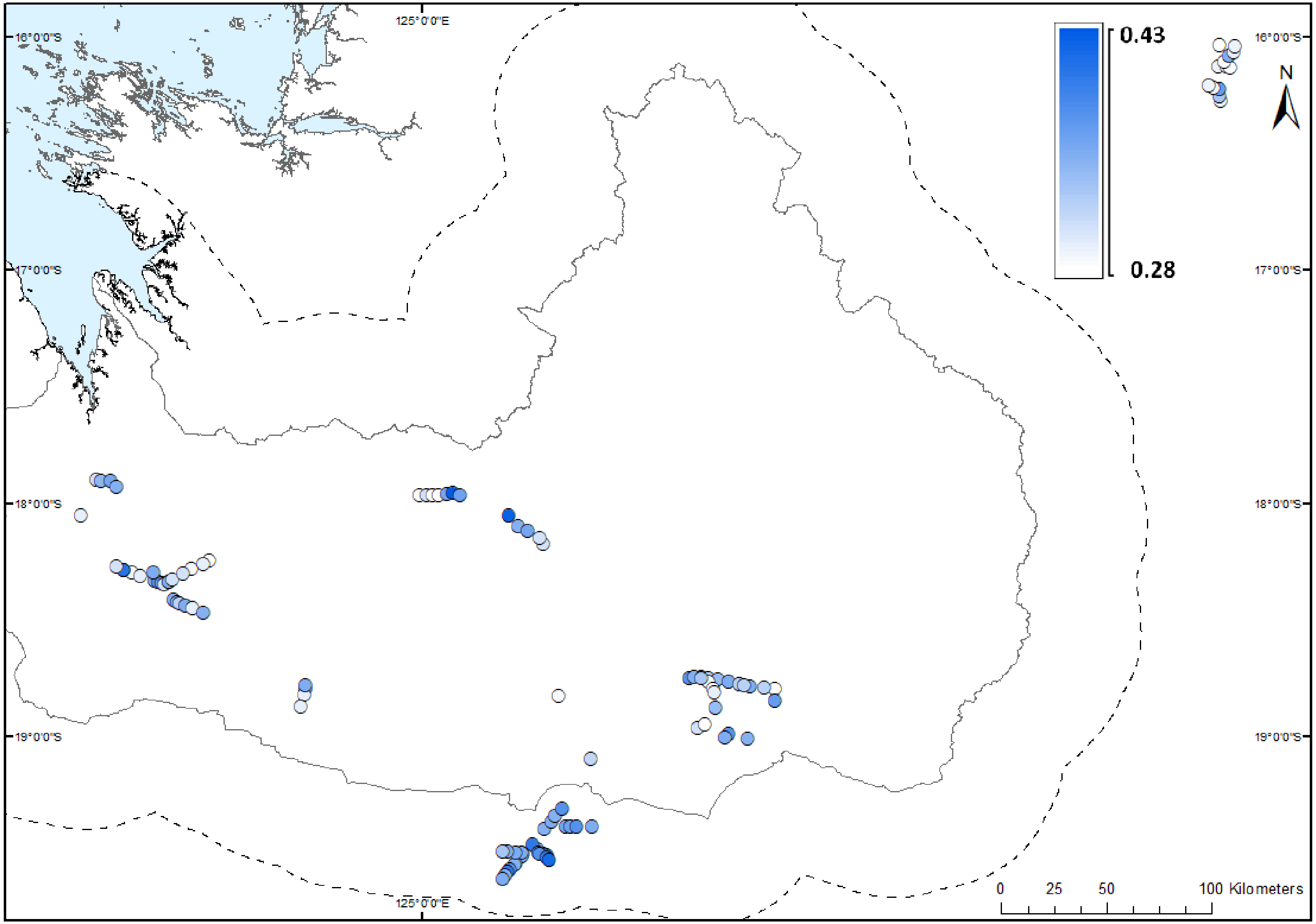

Figure 3.16. Standard error of model averaged estimate for probability of dingo presence at each surveyed plot.

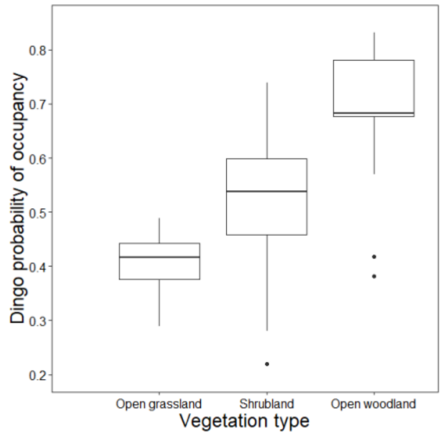

Figure 3.17. Model averaged dingo occupancy probability as a function of vegetation type.

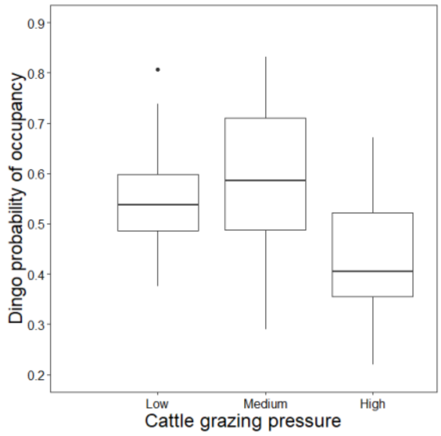

Figure 3.18. Model averaged dingo occupancy probability as a function of cattle grazing pressure.

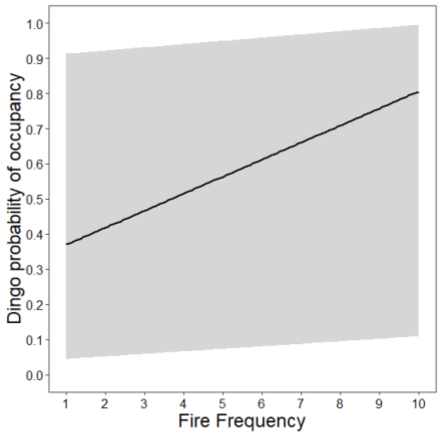

Figure 3.19. Model averaged dingo occupancy probability and 95% confidence interval, as a function of fire frequency.

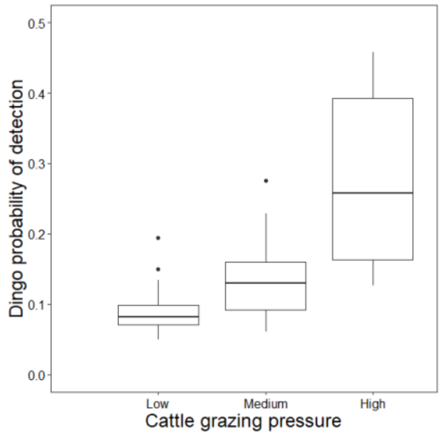

Figure 3.20. Model averaged dingo detection probability as a function of cattle grazing pressure.

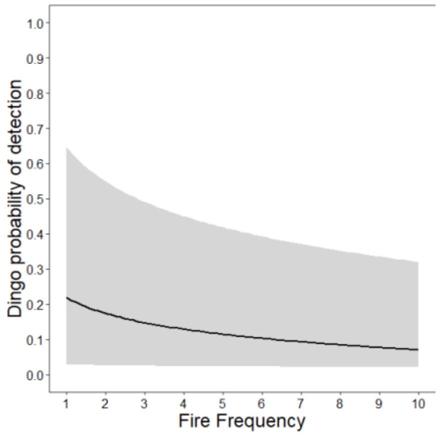

Figure 3.21. Model averaged dingo detection probability and 95% confidence interval, as a function of fire frequency.

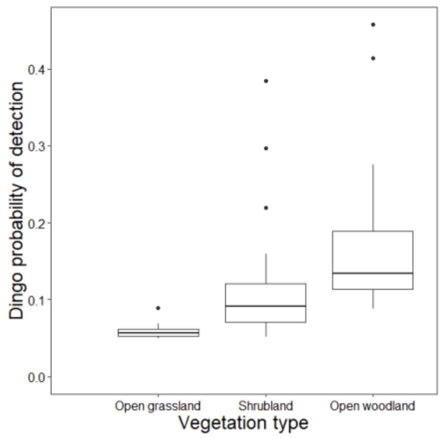

Figure 3.22. Model averaged dingo detection probability as a function of vegetation type.

3.1.4 Cattle

A total of 88 detections of cattle (*Bos taurus*) sign were observed at 48 unique plots.

Based on the estimated occupancy and detection probabilities from the simplest model, cattle occupancy was estimated at 0.48 (± 0.05 SE) with a per survey detection probability of 0.56 (± 0.05 SE). The mean model averaged occupancy using the top five models was estimated at 0.49 (± 0.09 SE) and the per survey detection probability at 0.54 (± 0.08 SE).

The five highest-ranked models from model fitting are shown in Table 3.5. Model averaged estimates of the occupancy probability at each plot are mapped in Figure 3.23, with associated standard errors presented in Figure 3.24. The results of the model fitting indicate that a combination of vegetation type and fire frequency influenced cattle occupancy and that vegetation type and fire frequency best described the detection of cattle at occupied plots.

Cattle occupancy probability was estimated to be highest in open woodland and lowest in open grassland (Figure 3.25) and increased with fire frequency (Figure 3.26). Cattle detection probability was estimated to be highest in open woodland and lowest in open grassland (Figure 3.27) and to increase with fire frequency (Figure 3.28).

Table 3.5. Summary of the five highest-ranked models compared using Akaike information criterion (AIC) for cattle occupancy and detection.

Model number	Model	AIC	ΔAIC	Negative 2 loglikelihood	Number of parameters	Weight
9	psi(Veg_cov+Fire_freq)p(Veg_cov)	327.2810	0	317.2810	5	0.2281
12	psi(Veg_cov+Fire_freq)p(.)	327.2870	0.0060	319.2870	4	0.2274
5	psi(Fire_freq)p(Veg_cov)	328.1658	0.8848	320.1658	4	0.1465
10	psi(Veg_cov+Fire_freq)p(Fire_freq)	329.2146	1.9336	319.2146	5	0.0867
11	psi(Veg_cov+Fire_freq)p(Veg_cov+Fire_freq)	329.2600	1.9790	317.2600	6	0.0848

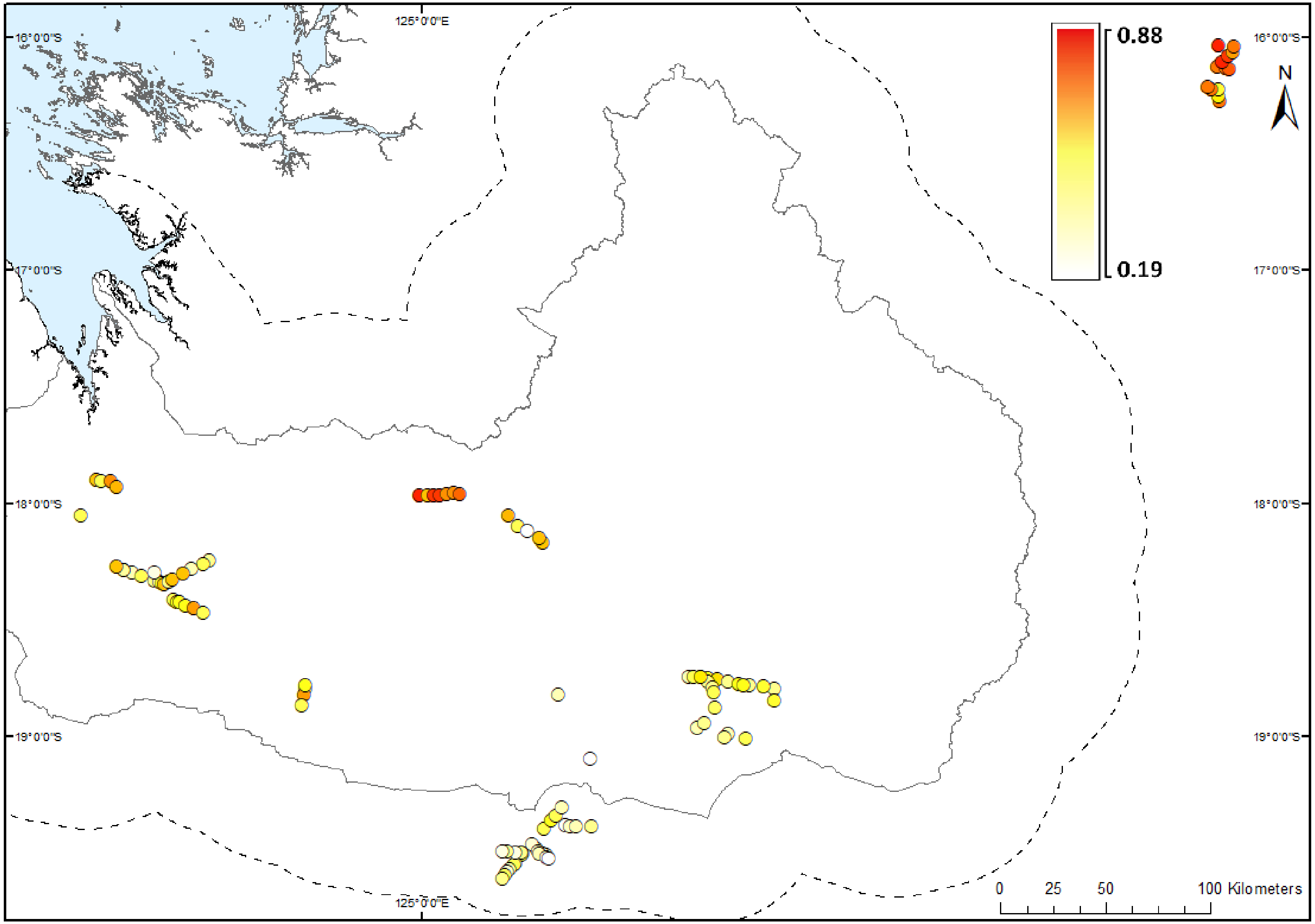

Figure 3.23. Model averaged estimate for probability of cattle presence at each surveyed plot.

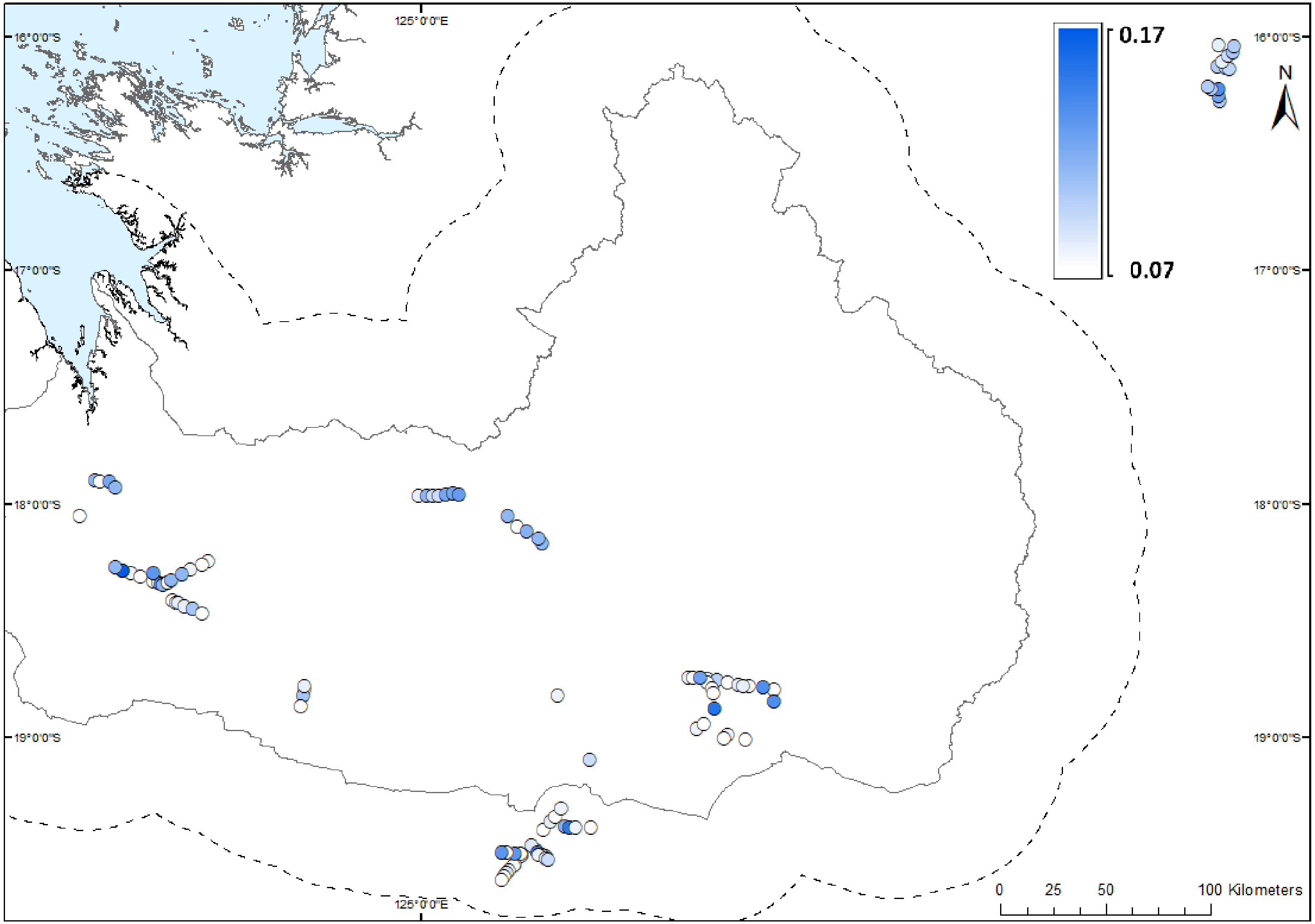

Figure 3.24. Standard error of model averaged estimate for probability of cattle presence at each surveyed plot.

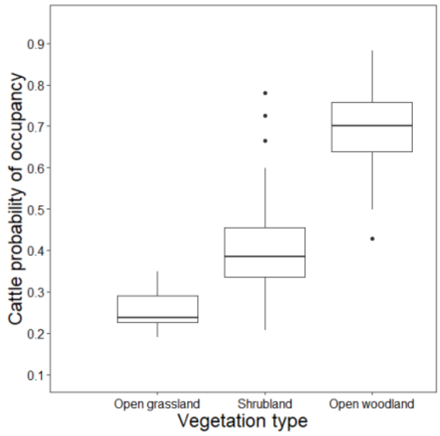

Figure 3.25. Model averaged cattle occupancy probability as a function of vegetation type.

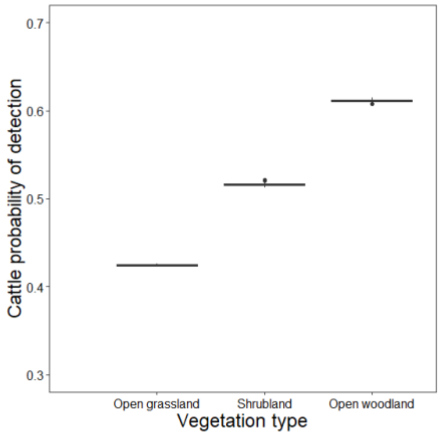

Figure 3.27. Model averaged cattle detection probability as a function of vegetation type.

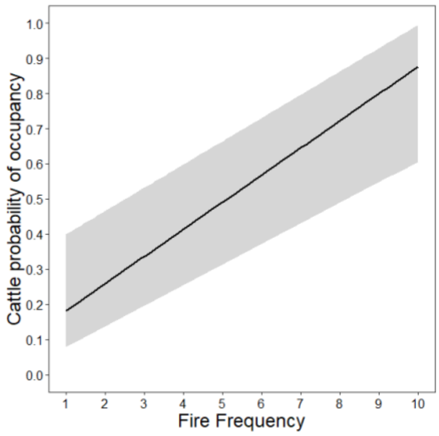

Figure 3.26. Model averaged cattle occupancy probability and 95% confidence interval, as a function of fire frequency.

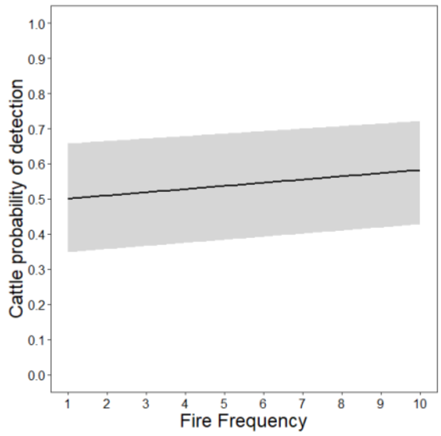

Figure 3.28. Model averaged cattle detection probability and 95% confidence interval, as a function of fire frequency.

3.1.5 Feral dromedary camel

A total of 65 detections of camel (*Camelus dromedarius*) sign were observed at 36 unique plots.

Based on the estimated occupancy and detection probabilities from the simplest model, with no covariates on either component, camel occupancy was estimated at 0.37 (± 0.05 SE) with a per survey detection probability of 0.55 (± 0.06 SE). The mean model averaged occupancy using the top five models was estimated at 0.39 (± 0.07 SE) and the per survey detection probability at 0.52 (± 0.13 SE).

The five highest-ranked models from model fitting are shown in Table 3.6. Model averaged estimates of the occupancy probability at each plot are mapped in Figure 3.29, with associated standard errors presented in Figure 3.30. The results of the model fitting indicate that a combination of cattle grazing pressure, vegetation type and fire frequency influenced camel occupancy and that vegetation type, cattle grazing pressure and fire frequency best described the detection of camel at occupied plots.

Camel occupancy probability was estimated to be highest when cattle grazing pressure is low (Figure 3.31), decreased with increasing fire frequency (Figure 3.32) and was highest in open grassland and lowest in open woodland (Figure 3.33). Camel detection probability was estimated to be highest in open woodland and lowest in open grassland (Figure 3.34), highest with low cattle grazing pressure (Figure 3.35), and tended to increase with fire frequency, but with uncertainty (Figure 3.36).

Table 3.6. Summary of the five highest-ranked models compared using Akaike information criterion (AIC) for camel occupancy and detection.

Model number	Model	AIC	ΔAIC	Negative 2 loglikelihood	Number of parameters	Weight
49	psi(Grazing_cov+Fire_freq+Veg_cov)p(Veg_cov)	234.8437	0	222.8437	6	0.1728
53	psi(Grazing_cov+Fire_freq+Veg_cov)p(Grazing_cov+Veg_cov)	235.1916	0.3479	221.1916	7	0.1452
50	psi(Grazing_cov+Fire_freq+Veg_cov)p(Grazing_cov)	235.7037	0.8600	223.7037	6	0.1124
56	psi(Grazing_cov+Fire_freq+Veg_cov)p(.)	235.7366	0.8929	225.7366	5	0.1105
54	psi(Grazing_cov+Fire_freq+Veg_cov)p(Veg_cov+Fire_freq)	236.7910	1.9473	222.7910	7	0.0653

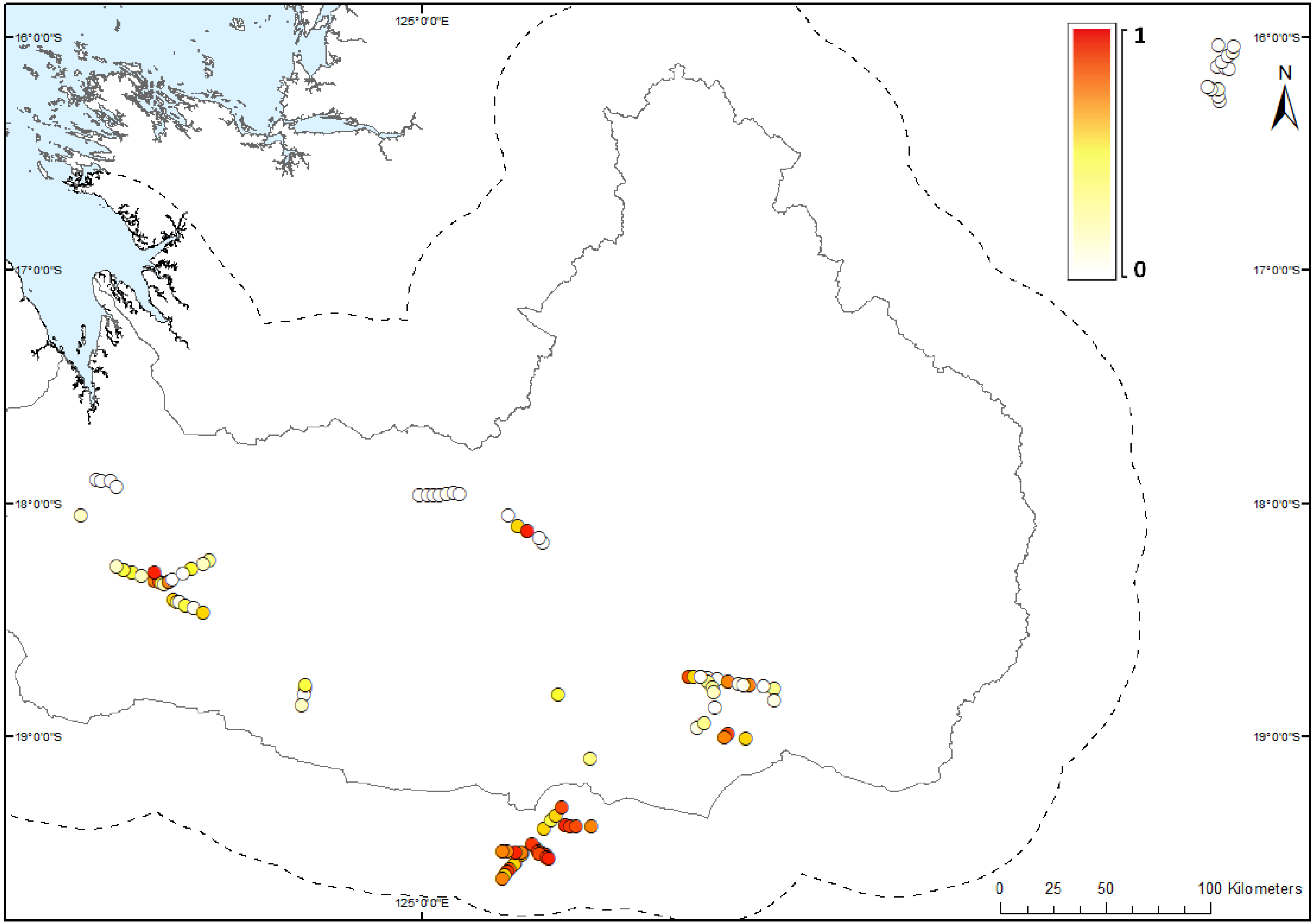

Figure 3.29. Model averaged estimate for probability of camel presence at each surveyed plot.

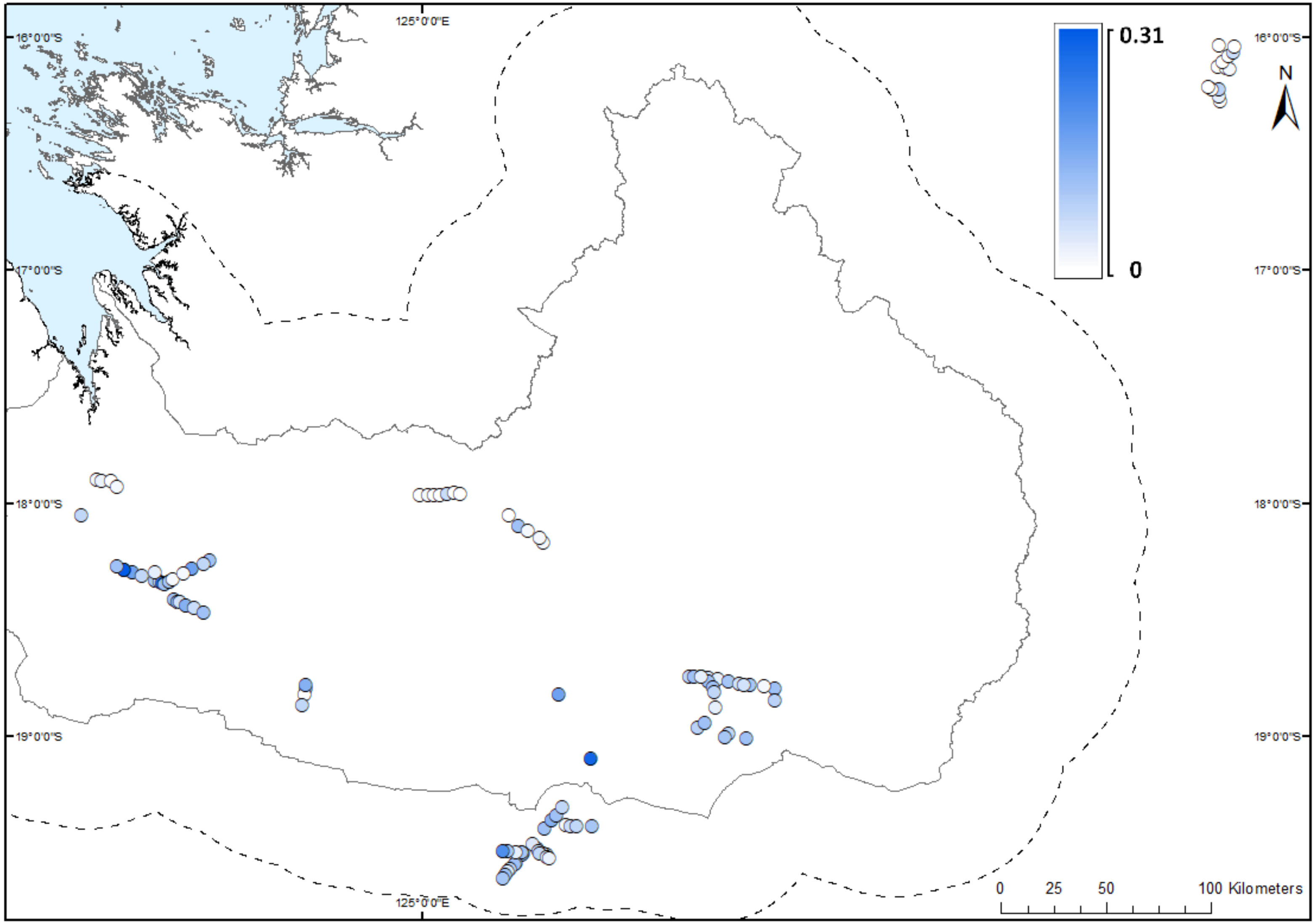

Figure 3.30. Standard error of model averaged estimate for probability of camel presence at each surveyed plot.

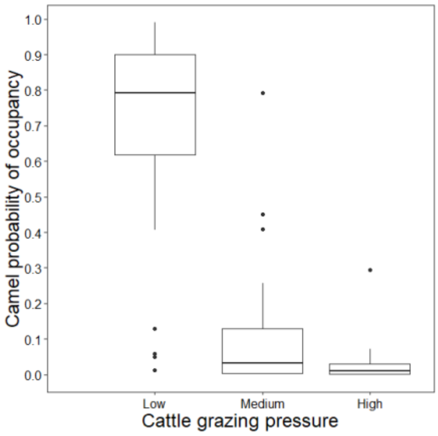

Figure 3.31. Model averaged camel occupancy probability as a function of cattle grazing pressure.

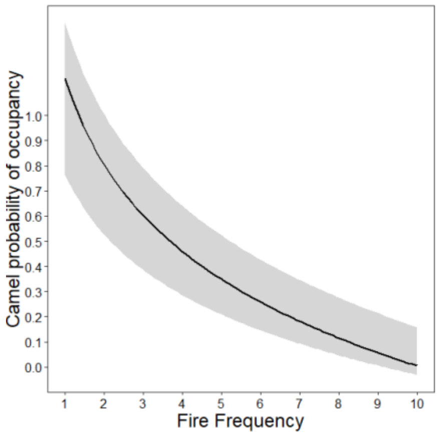

Figure 3.32. Model averaged camel occupancy probability and 95% confidence interval, as a function of fire frequency.

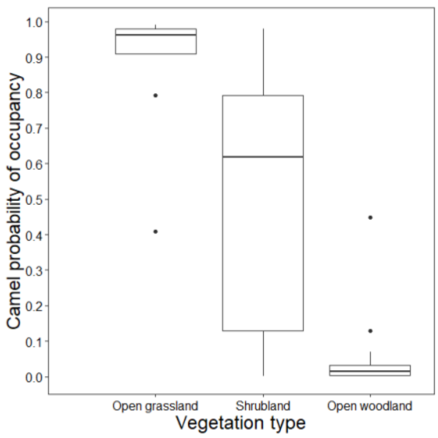

Figure 3.33. Model averaged camel occupancy probability as a function of vegetation type.

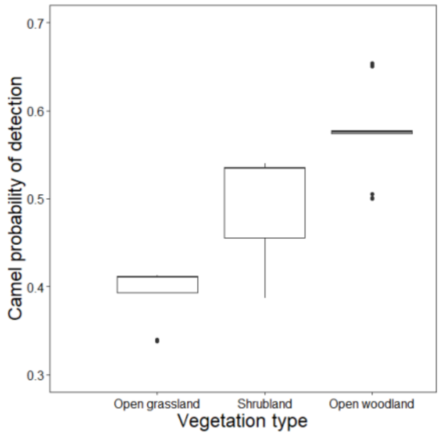

Figure 3.34. Model averaged camel detection probability as a function of vegetation type.

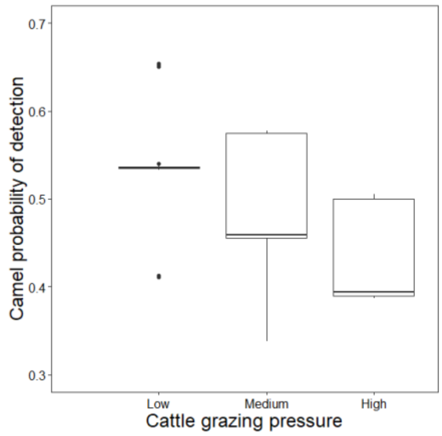

Figure 3.35. Model averaged camel detection probability as a function of cattle grazing pressure.

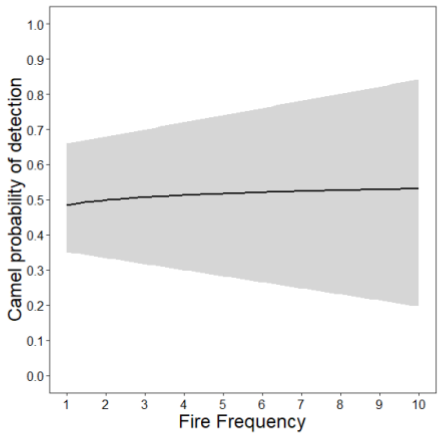

Figure 3.36. Model averaged camel detection probability and 95% confidence interval, as a function of fire frequency.

3.1.6 Feral horse

A total of eight detections of feral horse (*Equus ferus*) sign (regardless of age) were observed at eight unique plots. There were not enough observations to undertake occupancy analyses. Feral horses were only present in the north-east of the project area on plots surveyed by Kija Rangers (Figure 3.37).

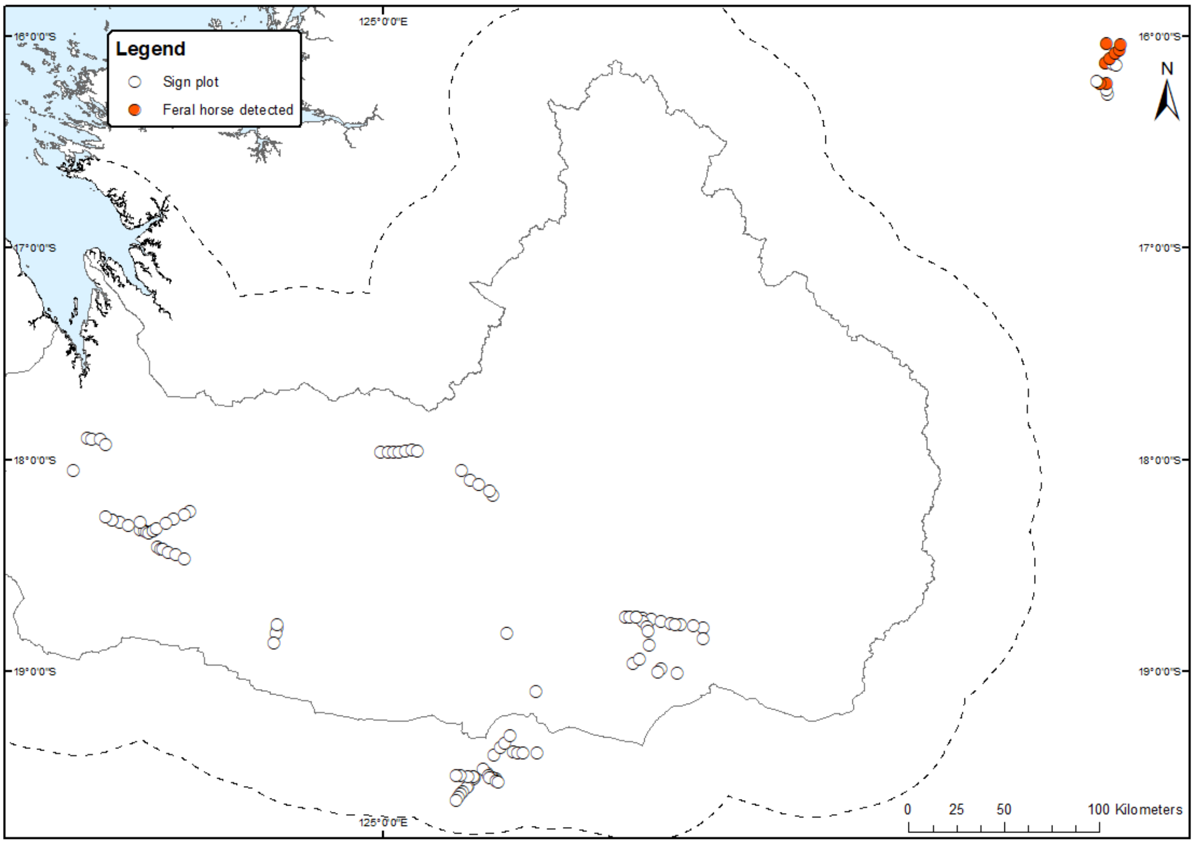

Figure 3.37. Feral horse detections on 2 ha sign plots in the project area.

3.1.7 Red fox

One detection of a fox (*Vulpes vulpes*) was observed on sign plots during occupancy surveys. The tracks of a fox were identified on plot NG03 (Purluwarla) surveyed by Ngurrara Rangers (Figure 3.38).

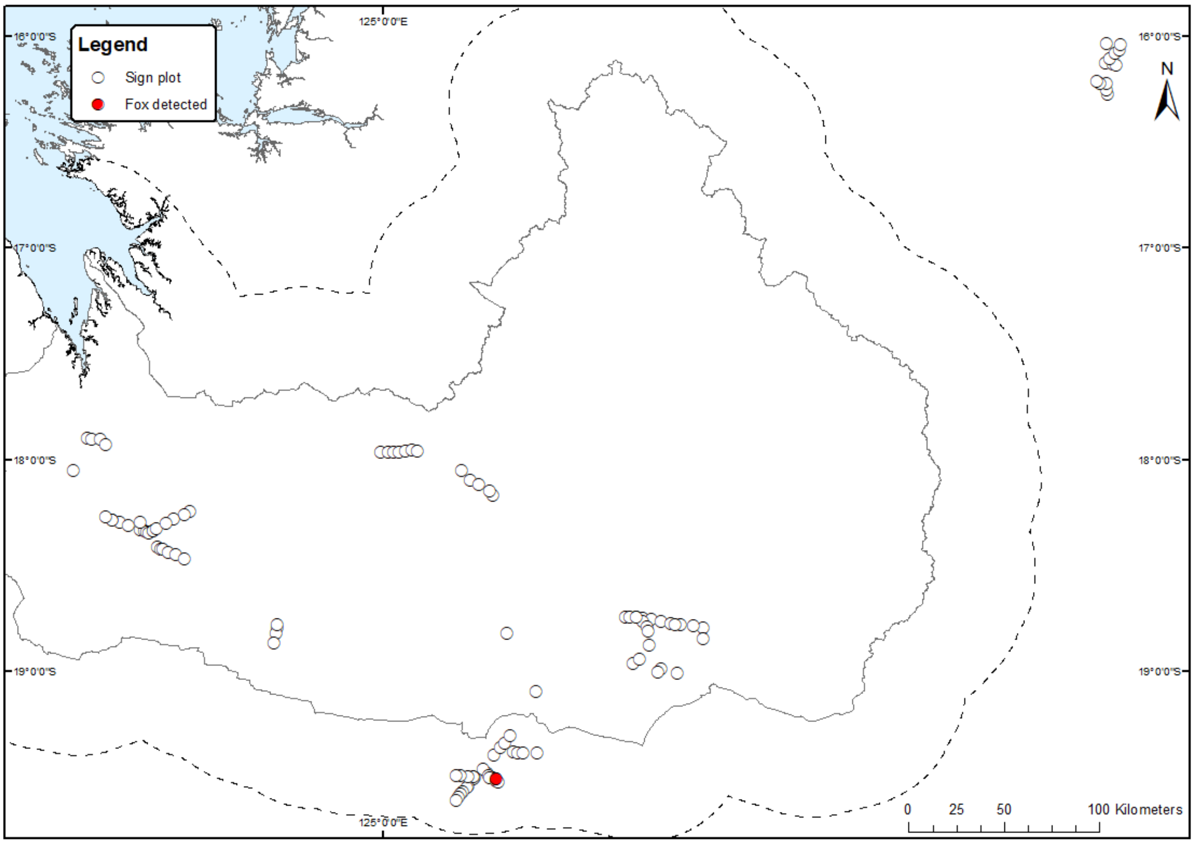

Figure 3.38. Fox detection on sign plot NG03 (Purluwarla) in the project area.

3.2 Predator occupancy at bilby populations using cameras

Feral cats and foxes were recorded stationed at bilby burrows by day and night. No dingoes were recorded at bilby burrows (Figure 3.39).

3.2.1 Feral cat

Feral cats were detected at all sites. Occupancy derived from cameras was high, ranging from 0.67 (± 0.19 SE) to 1.00, with no differences in detection between cameras on vehicle tracks and cameras on burrows (Table 3.7; 0).

Table 3.7. Model comparisons of cameras on vehicle tracks and on bilby burrows for cat detection.

Model	ΔAIC	Weight	n Parameters	Negative 2 loglikelihood
psi(.)p(.)	0	0.67	2	174.89
psi(.)p(On_tracks)	1.37	0.33	3	174.26

AIC = Akaike information criterion

3.2.2 Red fox

Foxes were detected at Yarri Yarri (Nyikina Mangala) and Bawoorrooga (Gooniyandi). Occupancy derived from cameras ranged from 0.20 (± 0.19 SE) to 0.51 (± 0.40 SE), with no differences in detection between cameras on vehicle tracks and cameras on burrows (Table 3.8; 0).

Table 3.8. Model comparisons of cameras on vehicle tracks and on bilby burrows for fox detection.

Model	ΔAIC	Weight	n Parameters	Negative 2 loglikelihood
psi(.)p(.)	0	0.72	2	39.40
psi(.)p(On_tracks)	1.89	0.28	3	39.29

AIC = Akaike information criterion

3.2.3 Dingo

Dingos were only detected at Yarri Yarri (Nyikina Mangala) by cameras. Occupancy derived from cameras was 0.39 (± 0.24 SE; 0). Cameras on burrows did not detect any dingoes (Table 3.9).

Table 3.9. Model comparisons of cameras on vehicle tracks and on bilby burrows for dingo detection.

Model	ΔAIC	Weight	n Parameters	Negative 2 loglikelihood
psi(.)p(On_tracks)	0	0.62	3	25.95
psi(.)p(.)	1.01	0.38	2	28.96

AIC = Akaike information criterion

Figure 3.39. Feral cats, foxes and dingoes captured on remote cameras at bilby populations. Feral cats and foxes were recorded actively hunting at bilby burrows by day and night. No dingoes were recorded at bilby burrows.

3.3 Bilby abundance surveys

A total of 257 bilby scat samples (Figure 3.40) were collected along 55.7 km of transects across the three surveyed populations (Table 3.10).

Although genetic sampling within small areas of bilby activity such as Kurlku (Ngurrara) can provide a complete census of individuals present without the need to undertake SECR analyses, these analyses were implemented for consistency. Maximum likelihood SECR analyses (Table 3.11) revealed a comparatively large population of 13 individuals (Figure 3.41) at Bawoorrooga (Gooniyandi; Figure 3.42), and smaller populations at Kurlku (Ngurrara; Figure 3.43) and Yarri Yarri (Nyikina Mangala; Figure 3.44). Density was highest at Kurlku (Table 3.10).

Figure 3.40. A typical bilby digging and scat collected during bilby abundance surveys.

Table 3.10. Sampling parameters and maximum likelihood spatially explicit capture-recapture densities of bilbies at surveyed populations.

Population	Area (ha)	Number of scats collected	Genotyping success	Number of individuals detected on transects	Total transect effort (km)	Density (individuals/ha)	SE
Yarri Yarri (Nyikina Mangala)	1569	47	0.43	5	22.412	0.0038	0.0018
Kurlku (Ngurrara)	61	143	0.66	4	5.823	0.0690	0.0369
Bawoorrooga (Gooniyandi)	2202	67	0.72	12	27.464	0.0058	0.0017

SE = standard error

Table 3.11. Number of bilbies at each population derived from maximum likelihood spatially explicit capture-recapture analyses.

Population	Number of individuals	SE	5–95 % CI
Yarri Yarri (Nyikina Mangala)	6	2.8	2.5–14.5
Kurlku (Ngurrara)	4	2.2	1.6–11.1
Bawoorrooga (Gooniyandi)	13	3.8	7.2–22.6

CI = confidence interval; SE = standard error

Figure 3.41. Images of adult bilbies captured on remote cameras during the bilby abundance survey on Gooniyandi country.

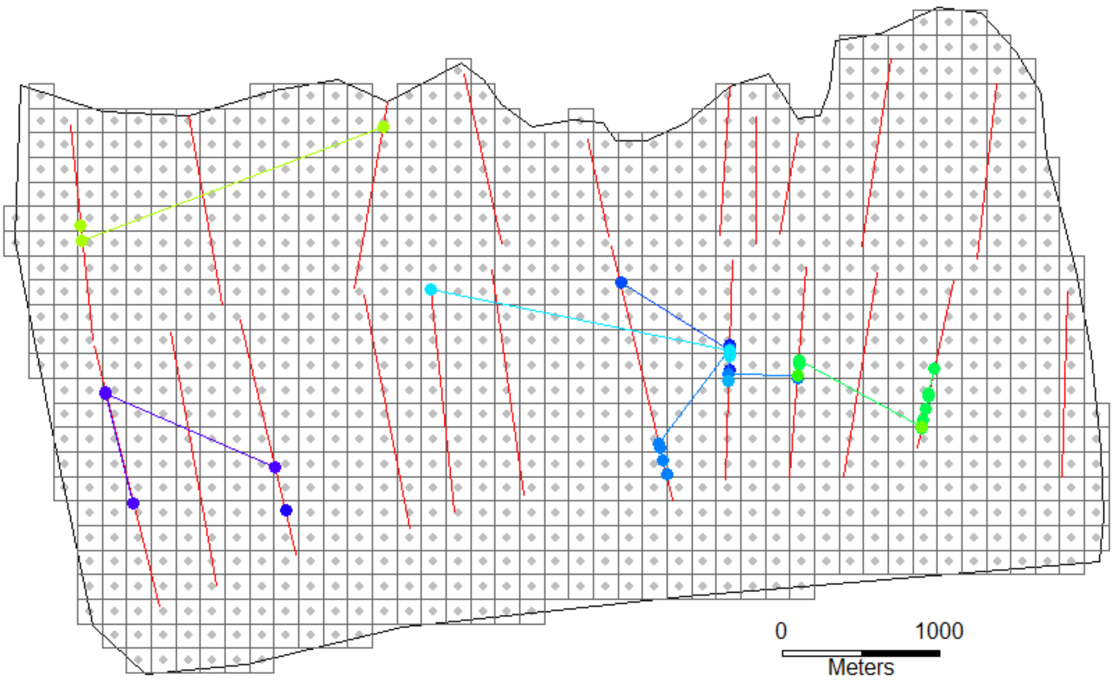

Figure 3.42. Spatial representation of data used in the maximum likelihood spatially explicit capture-recapture (SECR) analysis for the Bawoorrooga (Gooniyandi) population. Red lines represent transect detectors. The SECR integration mesh is represented in grey, and detections of individuals are colored points. The solid grey boundary represents the habitat mask.

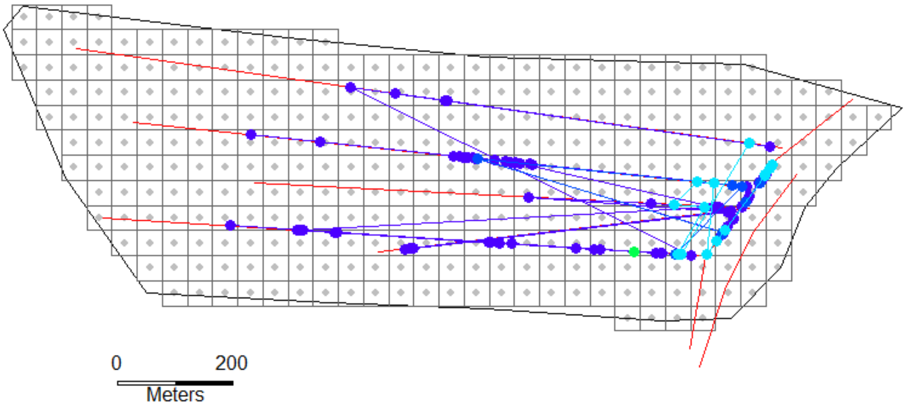

Figure 3.43. Spatial representation of data used in the maximum likelihood spatially explicit capture-recapture (SECR) analysis for the Kurlku (Ngurrara) population. Red lines represent transect detectors. The SECR integration mesh is represented in grey, and detections of individuals are colored points. The solid grey boundary represents the habitat mask.

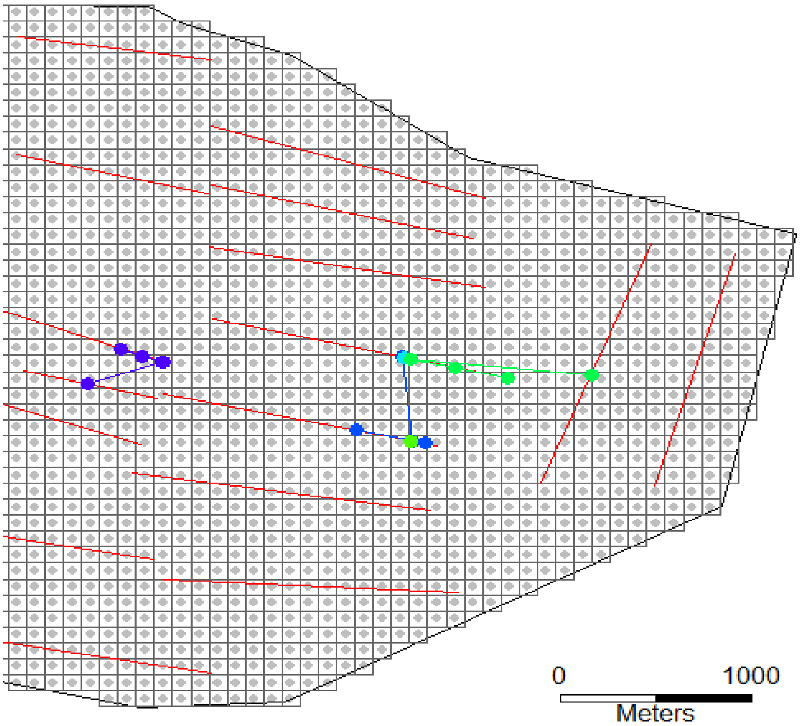

Figure 3.44. Spatial representation of data used in the maximum likelihood spatially explicit capture-recapture (SECR) analysis for the Yarri Yarri (Nyikina Mangala) population. Red lines represent transect detectors. The SECR integration mesh is represented in grey, and detections of individuals are colored points. The solid grey boundary represents the habitat mask.

3.4 Habitat suitability models

3.4.1 Variable selection

Correlated variables and those selected for further analyses are shown in Table 3.12. Variables used in the models, their importance as determined by permutation, and percent contribution are shown in Table 3.13 and Table 3.14.

Table 3.12. Variables selected to be included in Maxent modelling from groups of correlated variables.

Variable included	Correlated variables (excluded)	Test statistic and significance
		Spearman rank order correlation coefficient
Fire frequency	Bioclim18	0.578**
	Bioclim19	0.610**
	Prescott Index	0.601**
Sand	Clay	−0.926**
	Silt	−0.845**
Elevation	Depth of soil	−0.878**
	Relief 300 m radius	0.575**
		Pearsons χ^2
Vegetation type	Geology	2887.0***
	Soil type	2375.1***

***P*<0.01; ****P*<0.001

Table 3.13. Variables, their percent contribution and importance, used in the Maxent model including the categorical variable 'Vegetation type'.

Variable	Percent contribution	Permutation importance
Elevation	41.9	0
Vegetation type	40.8	0
Fire frequency	11.9	0
Depth of regolith	1.6	1.4
Sand	1.5	95.6
Coarse fragments	1.4	0.9
Available water capacity	0.8	1
Topographic wetness index	0.1	1.1

Table 3.14.Variables, their contribution and importance, used in the Maxent model excluding the categorical variable 'Vegetation type'.

Variable	Percent contribution	Permutation importance
Elevation	72.9	0
Fire frequency	16.7	0
Depth of regolith	2.8	0
Sand	2.3	97.3
Coarse fragments	2.3	1.6
Available water capacity	1.8	1.1
Topographic wetness index	1.1	0

3.4.2 Maxent model including the categorical variable 'Vegetation type'

The average test AUC for the replicate runs was 0.322 (± 0.032 standard deviation [SD]) for the model including the categorical variable 'Vegetation type'. The Maxent model indicates more suitable habitat in southern areas of the project area (Figure 3.45). The standard deviation of the habitat suitability index was low across much of the modelled area (Figure 3.46). The full Maxent output including specific effects of variables is included in Appendix 7.

3.4.3 Maxent model excluding the categorical variable 'Vegetation type'

The average test AUC for the replicate runs was 0.334 (± 0.027 SD) for the model excluding the categorical variable 'Vegetation type', indicating the model without vegetation type was slightly more robust. The Maxent model excluding vegetation type (Figure 3.47) appears in consensus with the model including vegetation type (Figure 3.45) and there is a general similarity between both models. The standard deviation of the habitat suitability index was also low across much of the modelled area (Figure 3.48). The full Maxent output including specific effects of variables is included in 0.

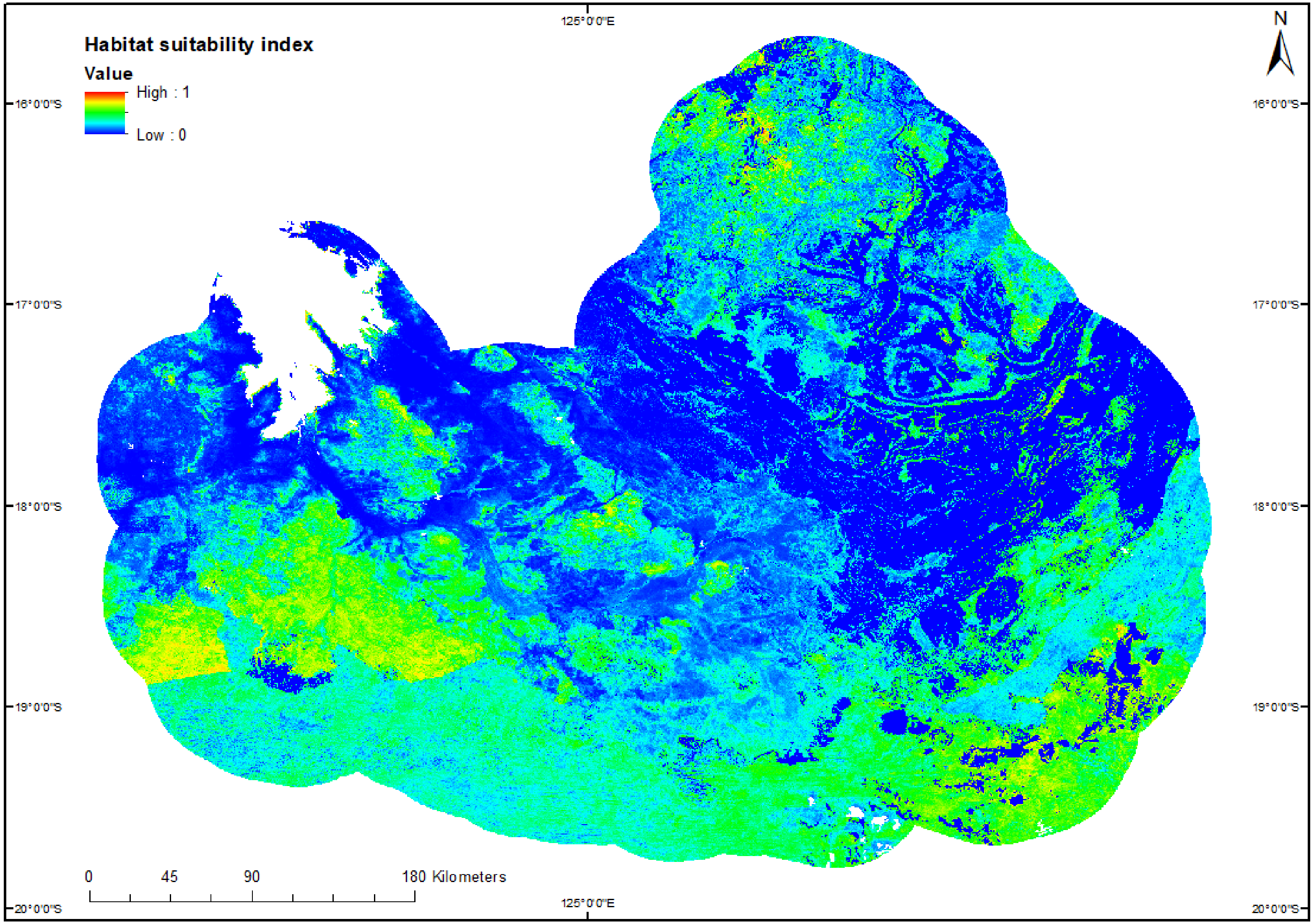

Figure 3.45. Maxent model of bilby habitat suitability. Model includes the categorical variable 'Vegetation type'.

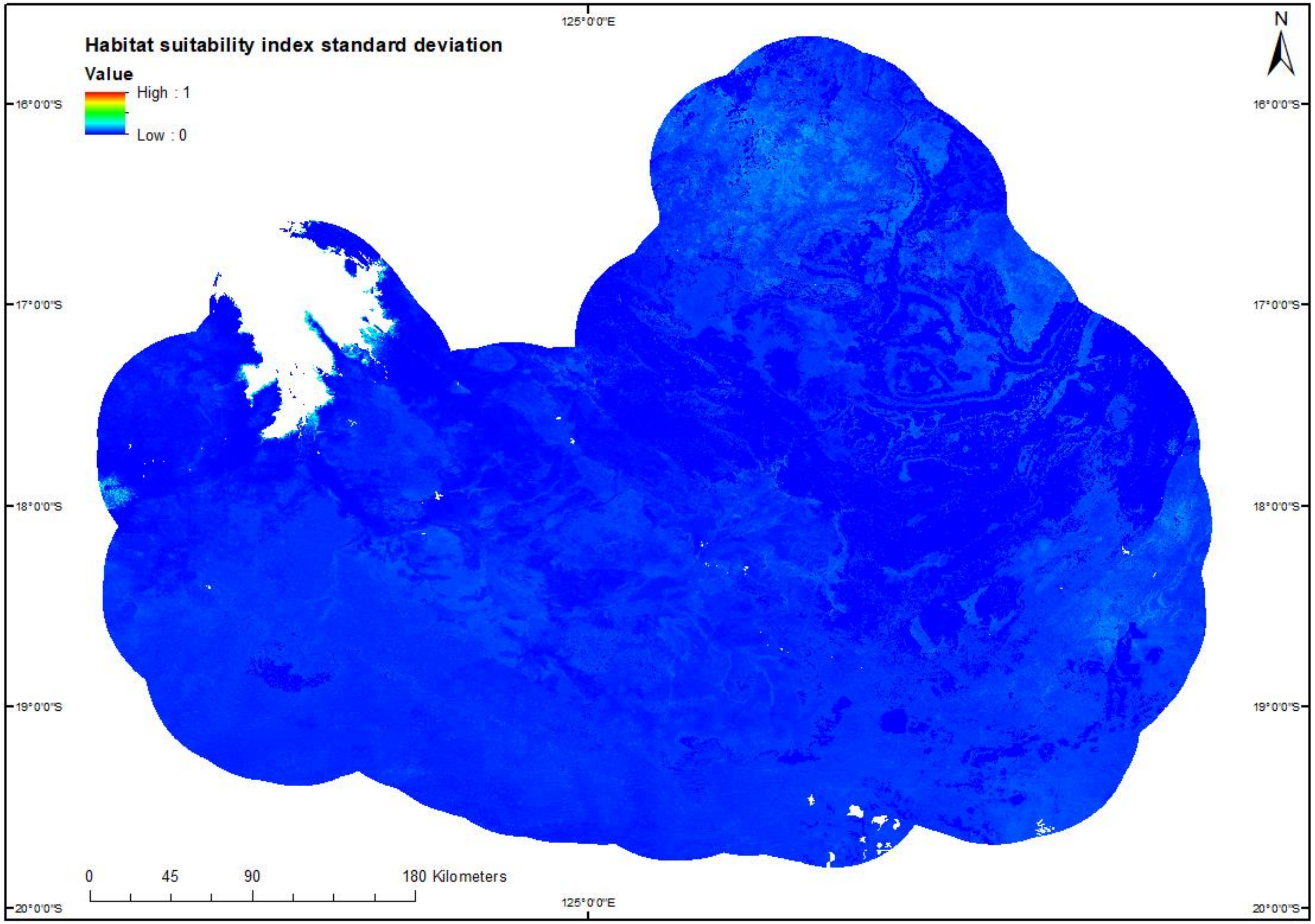

Figure 3.46. Maxent model of the standard deviation of bilby habitat suitability. Model includes the categorical variable 'Vegetation type'.

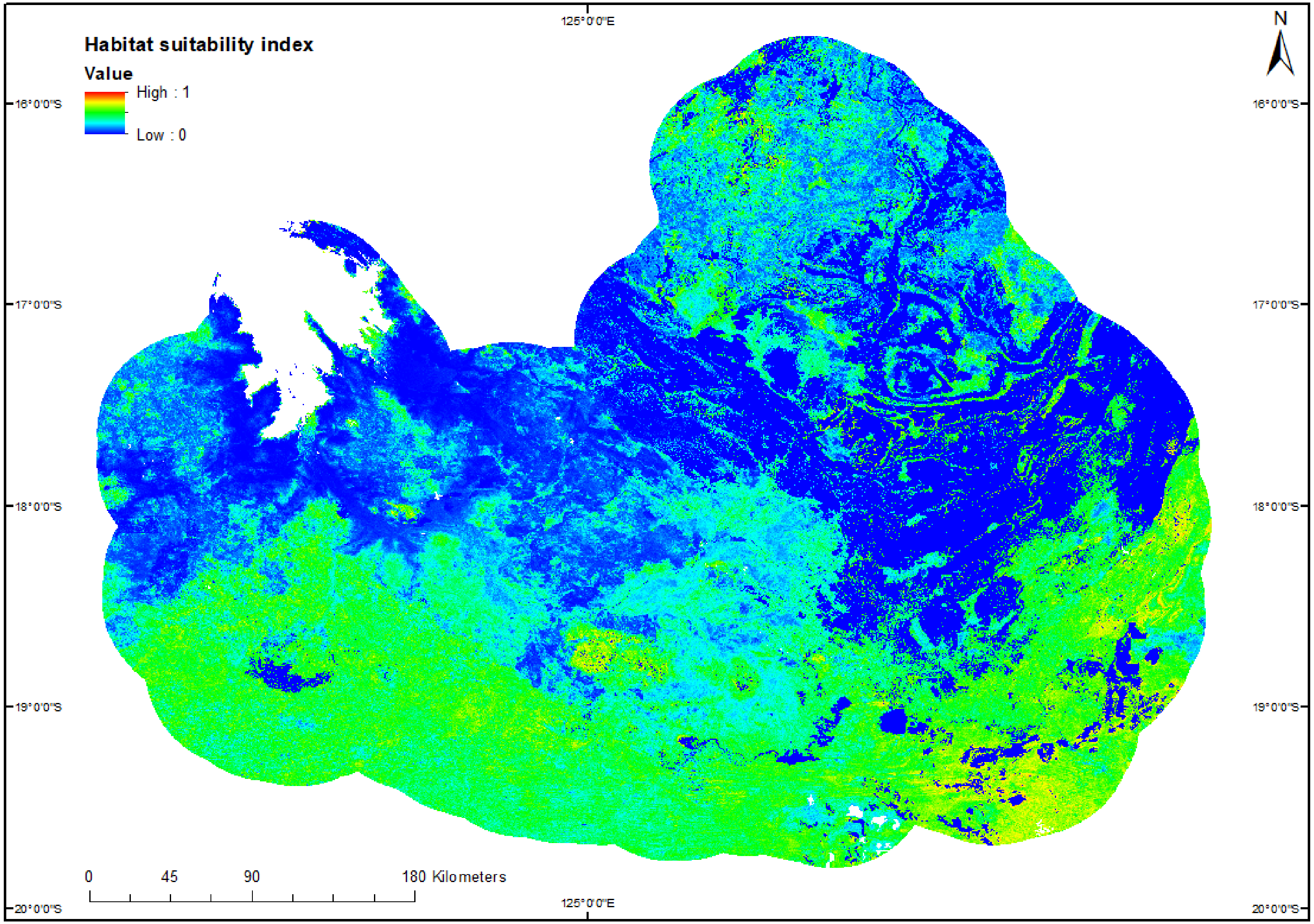

Figure 3.47. Maxent model of bilby habitat suitability. Model excludes the categorical variable 'Vegetation type'.

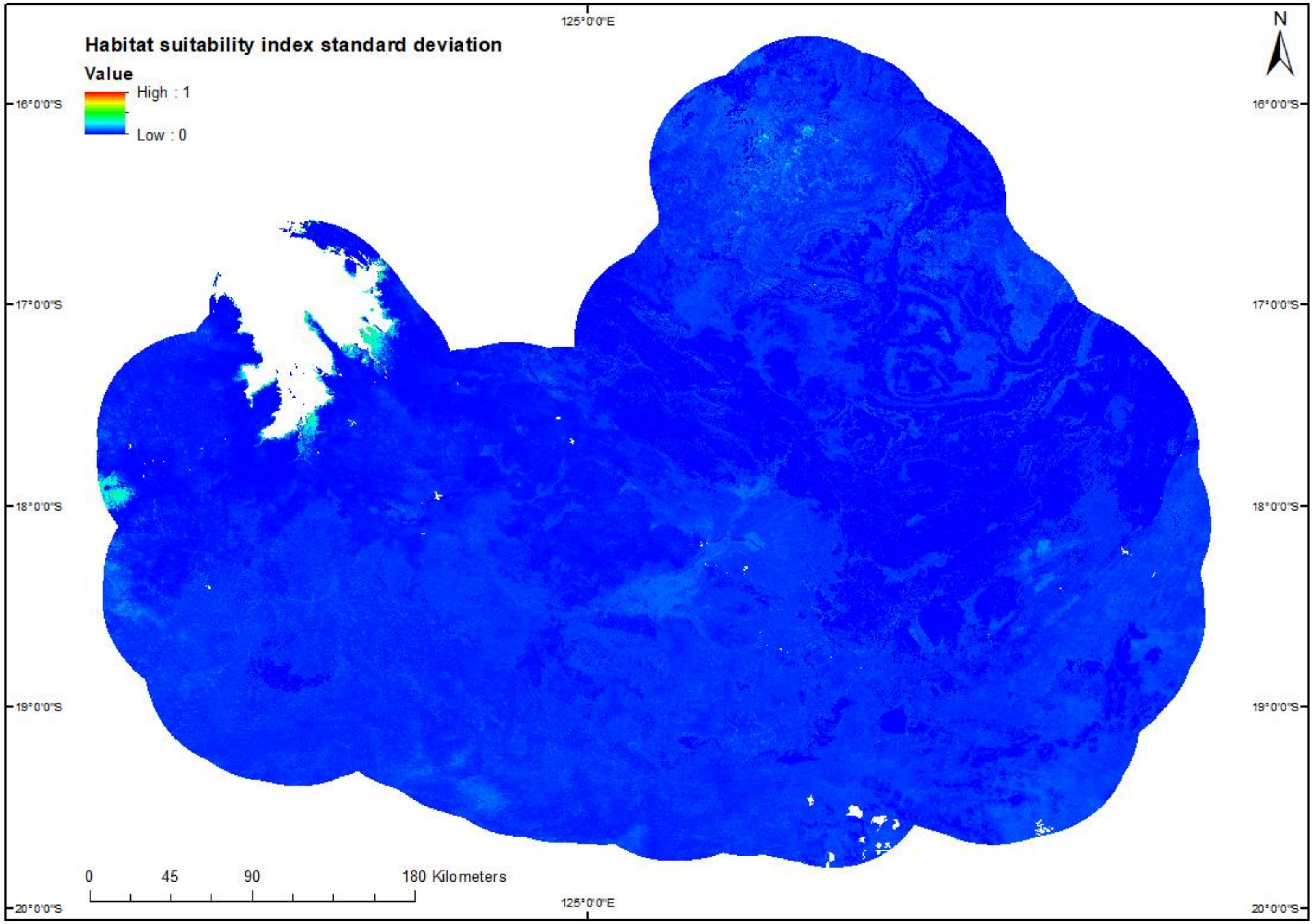

Figure 3.48. Maxent model of the standard deviation of bilby habitat suitability. Model excludes the categorical variable 'Vegetation type'.

3.5 Bilby population estimate for the project area

The Maxent model of bilby habitat suitability excluding the categorical variable 'Vegetation type' had a higher AUC and therefore was used to calculate the area (ha) of habitat with a suitability score of >0.5, noting that the predictive performance of the model was relatively low. The population size of bilbies within the project area was estimated at 11,806 (± 6,068 SE; Table 3.15).

Table 3.15. Figures used in the bilby population size estimate.

Total size of project area (ha)	Area of habitat suitability >0.5 (ha)	Mean model averaged occupancy	Mean density (individuals/ ha)	Mean SE	Population estimate	SE
15,251,123	2,145,685	0.21	0.0262	0.0135	11,806	6,068

SE = standard error

4. Discussion

4.1 Occupancy

The occupancy survey identified the probability of presence of bilbies and other key species that have been recognised as threats to bilby populations across the project area, using repeat surveys to account for imperfect detection. Based on the mean model averaged occupancy and detection probabilities, bilby occupancy was estimated at 0.21 with a per survey detection probability of 0.49. That is, bilbies used 21% of surveyed 2 ha plots in the Fitzroy catchment region, and given a plot is used by a bilby, the probability of finding evidence of that use in a single survey was 0.49.

Bilby occupancy in the Fitzroy catchment region is comparable to the La Grange area (west of the project area) where bilby occupancy was estimated at 0.22, with a detection probability of 0.42 (Dziminski et al*.* 2018). Bilby occupancy at Matuwa, which has had long-term fire management and control of feral cats by aerial Eradicat® baiting, was recorded at 0.32 (Lohr et al*.* 2021).

This study showed a clear negative relationship between bilby occupancy and cattle occupancy. Overgrazing by domestic cattle and other introduced herbivores has been implicated as a factor contributing to the decline of bilbies through the degradation of habitat. McDonald et al*.* (2015) reported that a competition refuge model best explained the range contraction of the bilby in the Northern Territory, with bilbies less likely to occur in grid cells where the dominant tenure was cattle grazing. Southgate (1990) likewise determined that bilby occurrence correlated with an absence or low abundance of livestock. Cattle disturbance has also been shown to have a negative association with small- to medium-sized mammals in other parts of the Kimberley (Radford et al*.* 2015).

Bilby detection was influenced by a combination of vegetation type and fire frequency, with a higher detection rate in open woodland plots subject to a higher fire frequency. A similar relationship was observed in the La Grange area (Dziminski et al*.* 2018), which may reflect the ease of detection in more open habitats.

Occupancy of feral cats on the plots within the project area was high at 0.91 (± 0.14 SE). Though occupancy was not calculated for the adjacent La Grange area, feral cats were detected on 59% of the surveyed plots (Dziminski et al*.* 2018). A study monitoring 2 ha sign plots in sandplain country in the Pilbara (Dziminski et al*.* 2021a) recorded feral cat occupancy at 0.51 (± 0.17 SE), and another study in the Fortescue Marsh recorded feral cat occupancy of up to 0.82 using remote cameras (Comer et al*.* 2018); bilbies are known to occur in both these areas. Feral cat occupancy detected by remote cameras at bilby populations in this study was also high at 0.8 (± 0.1 SE; across all sites combined), almost matching that observed in the Pilbara using the same technique of remote cameras on tracks and bilby burrows (0.91 ± 0.07 SE; Dziminski et al*.* 2021). During this study, feral cats were commonly observed actively preying and stationed at burrows occupied by bilbies (Figure 3.39). Collectively, these results suggest that bilbies are resilient to some level of feral cat presence. There was also no evidence that occupancy of dingoes influenced bilby occupancy, but interestingly, cat occupancy tended to decrease with increasing dingo occupancy.

A concerning finding of this study was the presence of foxes at the three monitored bilby populations. Foxes have been implicated as primarily responsible for the extirpation of bilbies in the southern portion of their former range across Australia (Southgate 1990) and a single fox can decimate a bilby colony (Bradley *et al.* 2015). Foxes were detected at Yarri Yarri (Nyikina Mangala) and Bawoorrooga (Gooniyandi) by remote cameras, and at Kurlku (Ngurrara) on a nearby plot. Fox occupancy derived from cameras ranged from 0.20 (± 0.19 SE) to 0.51 (± 0.40 SE) and was 0.23 (± 0.14 SE) across all bilby populations. Foxes were also recorded waiting at bilby burrows occupied by bilbies, sometimes for extended periods, even during daylight hours (Figure 3.39). Foxes were also frequently recorded near the coast in the La Grange area (Dziminski et al. 2018). It is a common misconception that foxes are not present in northern Australia, and hence do not pose a threat to bilby populations in this region. This study confirms the presence of foxes at bilby populations in the extreme north of the bilby's range, identifying them as a potential threat.

Only one fox (tracks) was identified on a sign plot by an experienced tracker and Traditional Owner elder at Kurlku (Ngurrara), whereas remote cameras more commonly detected foxes. Fox tracks can be difficult to distinguish from cat and small dingo tracks, though experienced trackers regularly identified fox tracks on sign plots in the La Grange area (Dziminski et al. 2018). This highlights the need for training and calibration of observers, particularly for future survey and monitoring (see 0).

Introduced predators (mainly feral cats) and herbivores (primarily cattle), both of which are recognised as threats to bilby populations (Woinarski et al. 2014; Bradley et al. 2015), were recorded extensively throughout the project area. These introduced animals place increased pressure on bilbies through predation, disease and habitat disturbance, which can result in decreasing bilby abundance and further dissection/fragmentation of sub-populations through local extinctions. The management of introduced predators and herbivores should be considered in any future management plan relating to bilbies in the Fitzroy catchment area (further details are provided in Section 4.5 below).

4.2 Abundance

Although focused on three discrete populations, the abundance survey showed that the population size and area of activity of bilbies varied in the Fitzroy catchment, ranging from 4 to 13 individuals. Population monitoring over several years in the Kimberley, Pilbara and central desert regions similarly recorded populations of approximately 2–15 individual bilbies (Dziminski et al. 2018; Dziminski et al. 2021b). Monitoring of three populations in the adjacent La Grange area estimated population sizes of 2, 10 and 44 individuals (Dziminski et al. 2018); the Anna Plains population in that area was determined to be the largest naturally occurring wild population of bilbies documented in Western Australia, and unusually occurring on coastal sand dunes.

4.3 Habitat suitability models

The two Maxent models were very similar. The variables contributing most to the models were elevation, vegetation type and fire frequency. The broad areas of higher habitat suitability identified by the Maxent models occur in the southern half of the Fitzroy catchment. The steep, complex rocky terrain to the north is generally considered not suitable habitat for bilbies and it may form a barrier to movement of animals into patches of potentially suitable habitat. There are no recent or historical bilby records in this northern area, and it is generally considered outside the bilby's range.

It should be acknowledged that the predictive performance of these models was low and based on only a few variables. Potentially important ecological variables that are thought to influence bilby distribution, such as predation pressure and effects of introduced herbivores, are missing from these models. However, bilbies are a generalist species that can utilise a variety of habitats and they are highly mobile; populations are known to move between surveys (Southgate and Carthew 2007; Southgate et al. 2007a).

4.4 Bilby population estimate for the project area

Based on data from occupancy, density and habitat suitability, the bilby population within the Fitzroy catchment region was estimated at 11,806 ± 6,068 individuals. This estimate should be interpreted with caution given the small number of plots sampled across the project area, a density estimate derived from just three populations and a poor-performing habitat suitability model.

4.5 Management recommendations

Although bilby populations are most likely to benefit from landscape-scale management, this is not always possible due to the large size of management areas, complications due to tenure, and availability of funding and resources. Management on a smaller scale, focusing on local bilby populations and/or key habitat, is also beneficial, and cumulatively over time and space, local management may eventually result in a landscape-scale program.

The area of management surrounding bilby populations should be large enough to create habitat heterogeneity and accommodate movement of the population within the managed area (Southgate and Possingham 1995; Southgate et al. 2007a; Southgate and Carthew 2007).

Dziminski and van Leeuwen (2019) discuss management to benefit bilbies on the Dampier Peninsula in the Kimberley, an area with similar threats to bilbies. The management actions discussed below align with the Interim Conservation Plan for the Greater Bilby (Bradley et al. 2015) and the draft National Bilby Recovery Plan, and are provided here as a guide to options for management.

4.5.1 Introduced predators

This study confirmed feral cats are widespread and common across the Fitzroy catchment. Cats prey on bilbies, and wherever wild bilby populations exist, cats are present. As suggested above, this means that bilby populations can tolerate a certain threshold of cat activity or abundance. Cats likely switch to preying on bilbies during periods when easier prey items become scarce, or during times when cat densities are high (Woinarski et al. 2014), or when both species are attracted to an area following fire (McGregor et al. 2016). Juvenile bilbies make easier prey and are likely targeted in preference to adults, resulting in decreased or negligible recruitment. This study also confirmed the occurrence of foxes in the project area, which are believed to have a larger impact on bilby populations than cats (Southgate et al. 2007b).

Details on feral cat management can be found in the *The Threat Abatement Plan for Predation by Feral Cats* (Commonwealth of Australia 2015). Recommendations summarised from the plan are:

- Shooting feral cats is expensive, labour intensive and time consuming and is typically only done on a relatively small scale.
- Like shooting, trapping as a control method is usually expensive, labour intensive and time consuming, and is only recommended on a small scale.
- Predator-proof fencing is expensive and requires ongoing maintenance to ensure its predator-proof integrity.
- Baiting for feral cats is a broadscale technique that has potential to reduce feral cat populations over larger areas. The Eradicat® bait is injected with 1080 and may be used in Western Australia under certain conditions. This bait is effective when applied strategically to target the feral cats when they are hungry (Christensen et al*.* 2013; Algar et al*.* 2013).

Furthermore, feral cat grooming traps (Felixers) are in the early stages of development, and may become another tool (Ecological Horizons 2019).

Landscape-scale actions

Annual strategic aerial Eradicat® baiting of large areas is likely to be effective (Algar and Burrows 2004; Algar et al*.* 2013; Doherty and Algar 2015). For example, long-term annual aerial Eradicat® baiting and supplementary trapping has allowed a reintroduced bilby population to rapidly expand and persist without fencing within the Matuwa Kurrara Kurrara Indigenous Protected Area (Lohr and Algar 2020; Lohr et al*.* 2021; Dziminski et al*.* 2021b). Baiting with Eradicat® is also likely to be effective for fox control.

Population-scale actions

Localised, strategic, limited aerial and/or ground baiting in the vicinity of managed bilby populations and in surrounding buffer zones, coupled with supplementary trapping (Molsher 2002; Algar et al*.* 2013) and traditional hunting (Taylor 2015), is likely to be an effective technique to control feral cats and foxes at and around bilby populations.

4.5.2 Interaction of fire and feral predators

In north-western Australia, cats strongly select areas recently burnt by intense fires, in habitats that typically support high abundance of small mammals (McGregor et al*.* 2014). Intense fires create conditions that are favoured by cats, probably because hunting success is improved (McGregor et al*.* 2014). Cats undertake expeditions of up to 12.5 km from their home ranges to hunt over recently burnt areas. Cats are especially likely to travel to areas burnt at high intensity and this behaviour increases the aggregate impact of cats on vulnerable prey (McGregor et al*.* 2016).

Fire management and burning at and around bilby populations may attract introduced predators to the existing bilby population. Therefore, best-practice management needs to manage both fire and introduced predators concurrently.

Landscape-scale actions

Fire management across selected large areas in the southern section of the Fitzroy catchment within suitable bilby habitat, with concurrent annual aerial Eradicat® baiting and targeted trapping/hunting, is recommended.

Population-scale actions

Localised fire management around bilby populations, such as fire breaks and patch mosaic burning, with concurrent annual targeted ground Eradicat® baiting and targeted trapping/hunting at bilby populations and in the buffer area, is likely to be effective. Conducting some burns in late spring or early summer would also improve *Yakirra* production (bilbies dig up and consume concentrations of the seeds of this plant that ants have harvested and stored; Figure 4.1).

4.5.3 Inappropriate fire regimes

Intense and large landscape-scale wildfires destroy, in a single event, large areas of habitat that provide food resources and cover from predation for bilbies. Such fires also remove food resources beyond the range of travel of the bilby and increases vulnerability to predation (Johnson 2008; Woinarski et al. 2014). Intense and large fires attract and result in an increase of feral cats from afar (McGregor et al. 2014; McGregor et al. 2016). On the other hand, if areas are left too long without burning, vegetation matures (i.e. ground cover vegetation approaches and exceeds 35%), and in these areas ground cover vegetation becomes largely impenetrable to bilbies (Bradley et al. 2015).

Bilby populations require smaller, more frequent fires that create a mosaic of different age classes of regrowth, which increase habitat and resource diversity (Southgate and Carthew 2006; Southgate and Carthew 2007; Southgate et al. 2007b).

Landscape-scale actions

Fire management across selected large areas in the southern section of the Fitzroy catchment within suitable bilby habitat is recommended.

Population-scale actions

Localised fire management around bilby populations, such as fire breaks and patch mosaic burning, with some burns in late spring or early summer to improve *Yakirra* production (Figure 4.1), is recommended. Establishing and maintaining a suitable firebreak surrounding the managed area (which should include a patch burn mosaic) to prevent large wildfires destroying vegetation structure and food resources (Wright and Clarke 2007) is an important consideration.

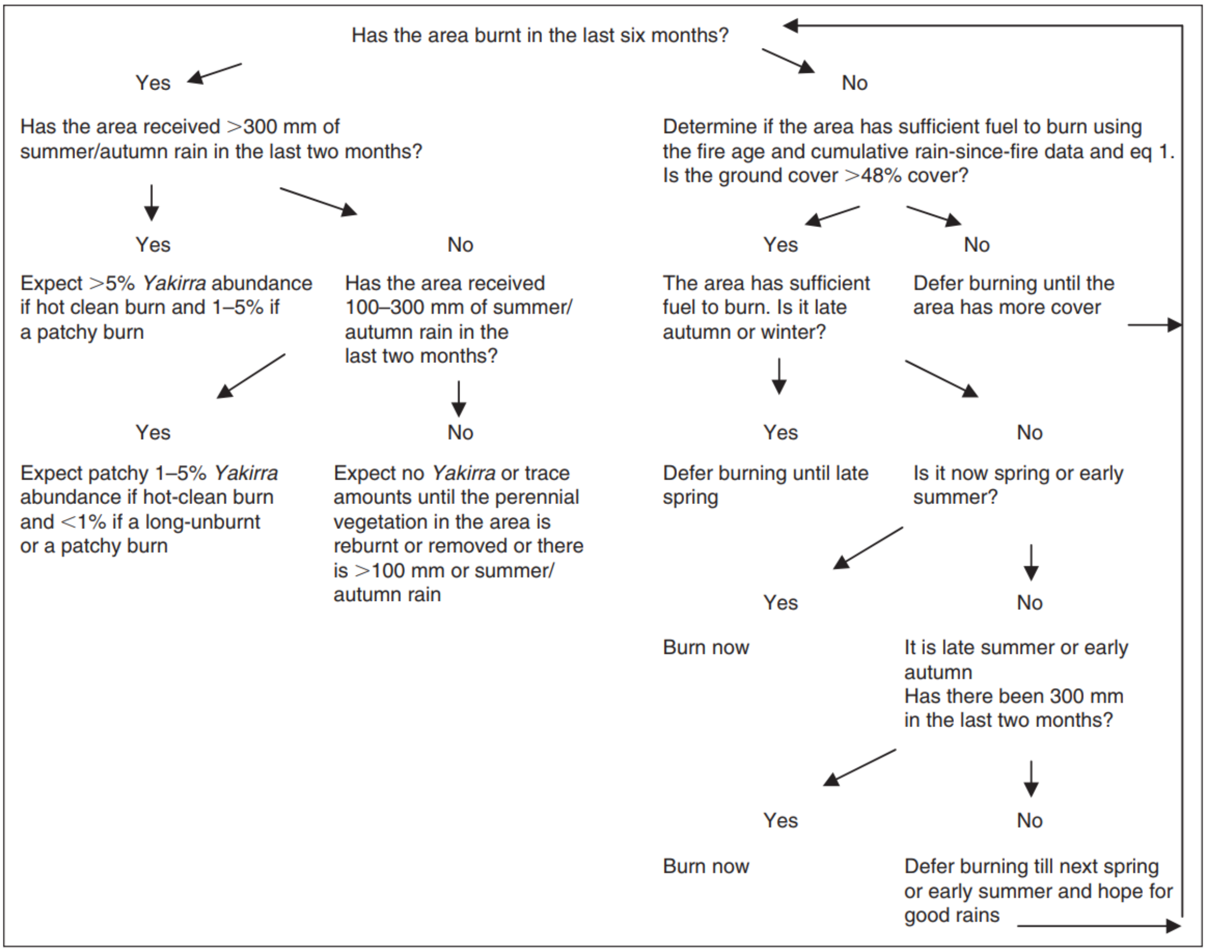

Figure 4.1. A decision model for land managers to identify when to burn and the amount of Yakirra growth to expect in response to fire age and rainfall conditions. From Southgate and Carthew (2007).

4.5.4 Introduced herbivores

Introduced herbivores include feral species (e.g. feral goats, camels, donkeys, rabbits), and both unmanaged and domestic livestock. Introduced herbivores remove vegetative cover and cause soil compaction; these effects are greater closer to water points (Bradley et al. 2015). Herbivores also congregate along drainage lines, which can often be important bilby habitat. Free water availability associated with pastoralism, at artificial water points for stock, also enables cats and foxes to spread and persist during dry/humid seasons (Bradley et al. 2015).

Landscape-scale actions

Fencing off areas for bilbies is one option, although large areas are required to be fenced due to the mobility of bilby populations. Aerial culling of feral herbivores and unmanaged livestock over large areas coinciding with suitable bilby habitat is another option.

Population-scale actions

Opportunistic ground culling of feral herbivores and unmanaged livestock, and/or negotiating the closure of artificial water points in the vicinity of managed bilby populations, are management options to be considered.

4.5.5 Land clearing

The effects of land clearing are manifested on a local as well a landscape scale over an extended period of time. Localised clearing can lead to the loss of bilby populations and important bilby habitat, and linear infrastructure may affect movement and dispersal and lead to fragmentation and loss of geneflow between populations (eg Epps *et al.* 2005; Holderegger and Di Giulio 2010). Widespread land clearing over the long term (30–50 years), through the accumulation over time and space of localised land clearing for development, can lead to a gradual and unrecognised loss of function of an entire ecosystem (for example the Western Australian Wheatbelt: Saunders 1989; Hobbs 1993).

Landscape-scale actions

Careful management to ensure large tracts of connected suitable habitat remain to support wild bilby populations is likely to reduce the impacts of land clearing. Securing land specifically for bilby conservation could also be considered.

Population-scale actions

Avoidance of clearing of habitat near key bilby populations is recommended.

5. Conclusions

The implementation of standardised survey and monitoring techniques as used in this study permits comparison of bilby population size and persistence across their distribution over time. Here, the application of this approach allowed for the occupancy and abundance of bilbies in the Fitzroy catchment to be determined, with similarities to other areas in the Kimberley and Pilbara observed.

Bilby occupancy across the project area, coupled with large areas of potentially suitable habitat in the southern section, confirm the Fitzroy catchment region as important for the continued persistence of wild bilby populations, particularly considering the ongoing contraction in range and decreases in occupancy of the species across its distribution. The widespread presence of recognised threats to bilbies (foxes, feral cats and introduced herbivores) in the catchment also highlights the requirement for appropriate threat-management actions to benefit the bilby. This study provides a flagship example of the partnership between modern science and Traditional Biocultural Knowledge to deliver new knowledge critical for informing the effective conservation of a cultural icon.

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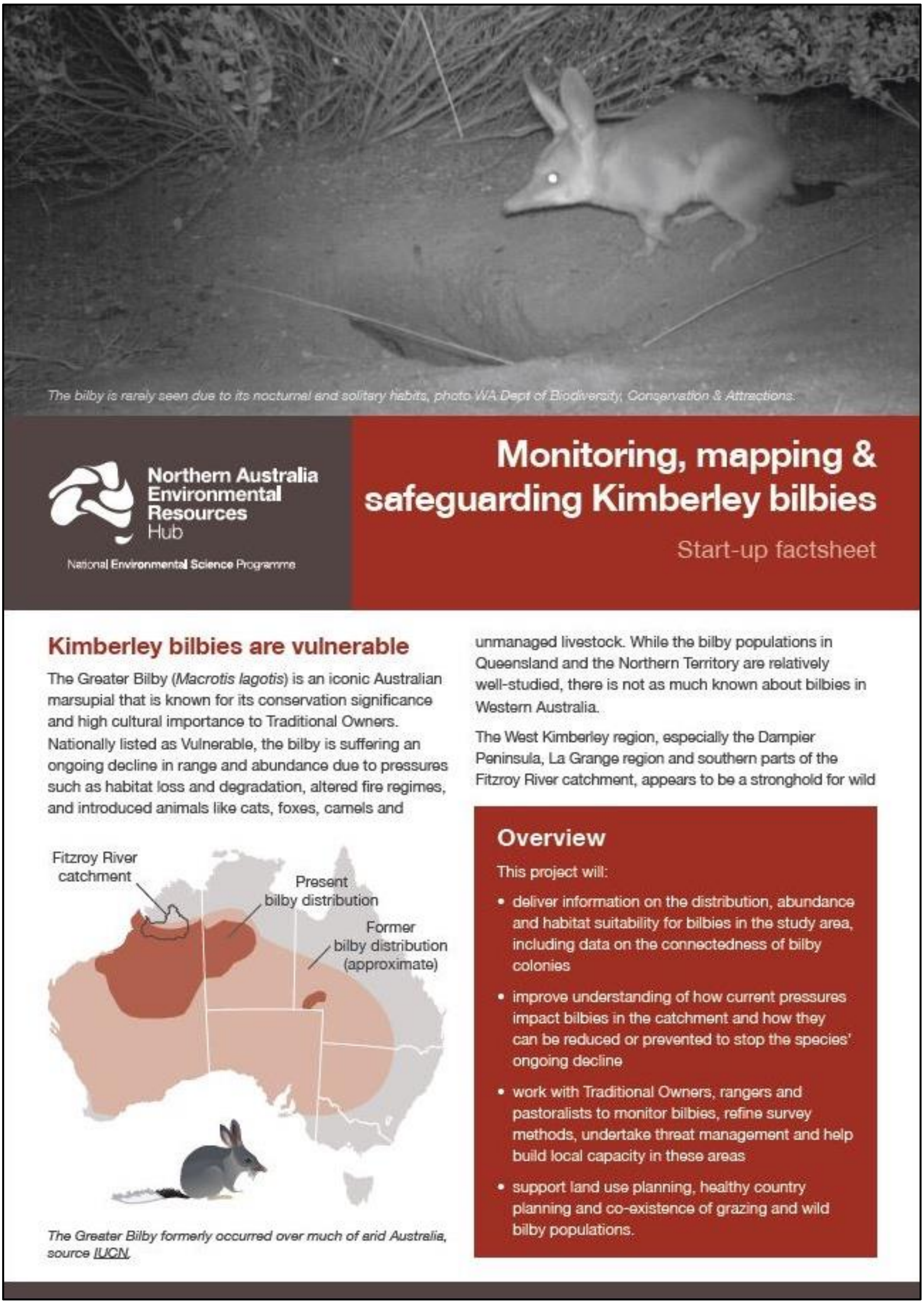
Appendix 1. Information sheet



The bilby is rarely seen due to its nocturnal and solitary habits, photo WA Dept of Biodiversity, Conservation & Attractions.

Northern Australia Environmental Resources Hub

National Environmental Science Programme

Monitoring, mapping & safeguarding Kimberley bilbies

Start-up factsheet

Kimberley bilbies are vulnerable

The Greater Bilby (*Macrotis lagotis*) is an iconic Australian marsupial that is known for its conservation significance and high cultural importance to Traditional Owners. Nationally listed as Vulnerable, the bilby is suffering an ongoing decline in range and abundance due to pressures such as habitat loss and degradation, altered fire regimes, and introduced animals like cats, foxes, camels and unmanaged livestock. While the bilby populations in Queensland and the Northern Territory are relatively well-studied, there is not as much known about bilbies in Western Australia.

The West Kimberley region, especially the Dampier Peninsula, La Grange region and southern parts of the Fitzroy River catchment, appears to be a stronghold for wild

The Greater Bilby formerly occurred over much of arid Australia, source IUCN.

Overview

This project will:

- deliver information on the distribution, abundance and habitat suitability for bilbies in the study area, including data on the connectedness of bilby colonies
- improve understanding of how current pressures impact bilbies in the catchment and how they can be reduced or prevented to stop the species' ongoing decline
- work with Traditional Owners, rangers and pastoralists to monitor bilbies, refine survey methods, undertake threat management and help build local capacity in these areas
- support land use planning, healthy country planning and co-existence of grazing and wild bilby populations.

bilby populations. Consequently, more data is needed from this region to inform land use planning and development decisions, as well as assist ongoing management.

Knowing more about bilbies in the Fitzroy River catchment can help protect them

In the Fitzroy River catchment, bilbies occur across a range of tenures such as pastoral leases, Native Title lands and conservation estates, and a collaborative approach is required to effectively conserve and manage the species. This project will bring together on-Country Traditional Owner land managers and researchers to build management capacity and help secure the future for bilbies in the Fitzroy River catchment. Project teams will collaborate with pastoralists to undertake studies of bilby populations and provide outcomes for effective coexistence of pastoral land use and the persistence of wild bilbies. This project will provide an accurate understanding of where bilbies occur and how they use their habitat in the Fitzroy River catchment. This information will be used to identify and implement on-ground actions that will help ease the impacts of threats to bilbies.

As well as gaining an understanding of the status of bilbies in the catchment, this project will contribute to species recovery planning and threat abatement programs. Broader natural resource management and conservation planning will also be supported through the research. The project will extend existing bilby research and management efforts and contribute to the Kimberley Bilby Network. It will also link with work outside the catchment, such as the Dampier Peninsula Bilby Offset Project and bilby projects in the Pilbara.

Project activities

- Assess the distribution and trends in occurrence and abundance of bilbies in the Fitzroy River catchment
- Investigate how bilbies use their habitat in the Fitzroy River catchment and relate this to habitat attributes and threats
- Reduce the impact of introduced predators on bilbies with an appropriate predator control program
- Assess the impacts of managing introduced predators, fire, grazing and other pressures on the bilby.

Anticipated outputs

- Management recommendations (e.g. for fire, grazing and pest control) based on an understanding of bilby distribution, abundance and habitat suitability to help ensure the co-existence of wild bilby populations and pastoralism
- Information on introduced predators and the response of bilby colonies to predator abatement actions
- Better data on bilbies for Traditional Owner databases and for portals such as NatureMap and the Atlas of Living Australia
- Factsheets, posters and presentations
- Peer-reviewed publications and technical reports.

Bilbies are now found predominantly in the driest and least fertile parts of their former range, photo Julie Burgher.

Who is involved?

This project will be managed by Dr Stephen van Leeuwen at the Western Australia Department of Biodiversity, Conservation and Attractions (DBCA). Dr van Leeuwen will be assisted by bilby scientist Dr Martin Dziminski and other researchers at DBCA, Traditional Owner ranger teams and the Kimberley Land Council.

Contact: stephen.vanleeuwen@dbca.wa.gov.au, 08 9219 9042.

For further information and project updates, visit the project webpage at www.nespnorthern.edu.au/projects/nesp/bilbies

Department of **Biodiversity, Conservation and Attractions**

Kimberley Land Council

This project is supported through funding from the Australian Government's National Environmental Science Program.

Northern Australia Environmental Resources Hub

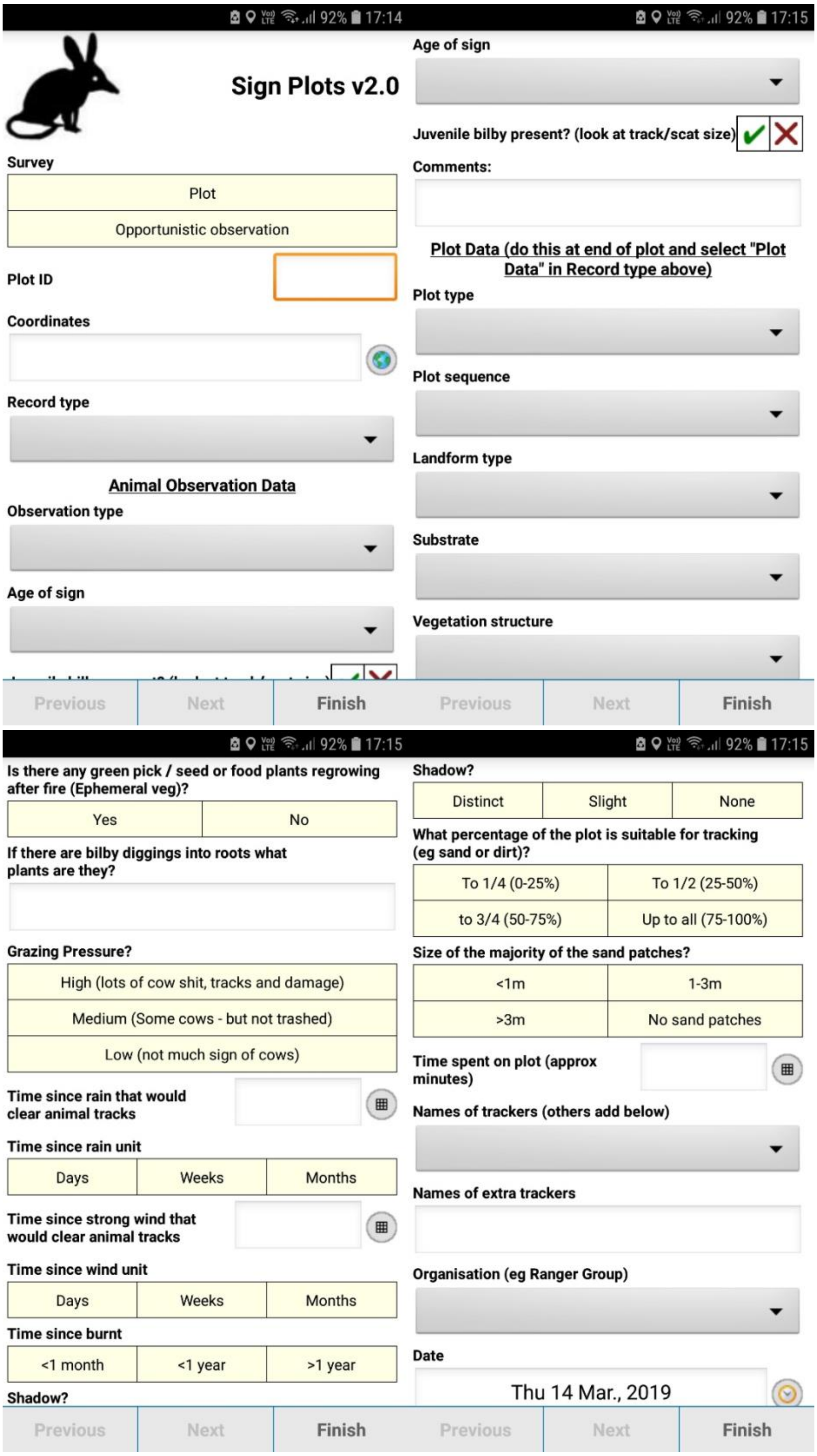
National Environmental Science Programme

nespnorthern.edu.au nesp.northern@cdu.edu.au

/NESPNorthern @NESPNorthern

September 2018

Appendix 2. Mobile Data Studio electronic input form for 2 ha sign plots



17:14

Sign Plots v2.0

Survey

Plot

Opportunistic observation

Plot ID

Coordinates

Record type

Animal Observation Data

Observation type

Age of sign

Previous | Next | Finish

17:15

Age of sign

Juvenile bilby present? (look at track/scat size)

Comments:

Plot Data (do this at end of plot and select "Plot Data" in Record type above)

Plot type

Plot sequence

Landform type

Substrate

Vegetation structure

Previous | Next | Finish

17:15

Is there any green pick / seed or food plants regrowing after fire (Ephemeral veg)?

Yes | No

If there are bilby diggings into roots what plants are they?

Grazing Pressure?

High (lots of cow shit, tracks and damage)

Medium (Some cows - but not trashed)

Low (not much sign of cows)

Time since rain that would clear animal tracks

Time since rain unit

Days | Weeks | Months

Time since strong wind that would clear animal tracks

Time since wind unit

Days | Weeks | Months

Time since burnt

<1 month | <1 year | >1 year

Shadow?

Previous | Next | Finish

17:15

Shadow?

Distinct | Slight | None

What percentage of the plot is suitable for tracking (eg sand or dirt)?

To 1/4 (0-25%) | To 1/2 (25-50%)

to 3/4 (50-75%) | Up to all (75-100%)

Size of the majority of the sand patches?

<1m | 1-3m

>3m | No sand patches

Time spent on plot (approx minutes)

Names of trackers (others add below)

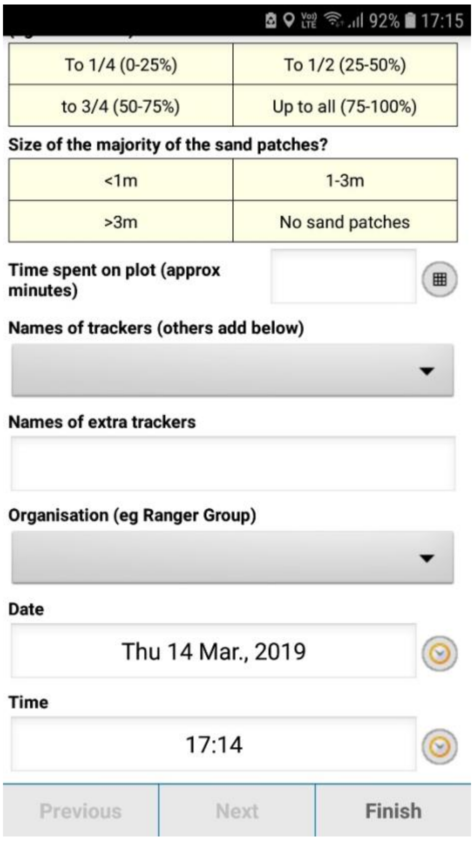
Names of extra trackers

Organisation (eg Ranger Group)

Date

Thu 14 Mar., 2019

Previous | Next | Finish


92% 17:15
To 1/4 (0-25%)
To 1/2 (25-50%)
to 3/4 (50-75%)
Up to all (75-100%)
Size of the majority of the sand patches?
<1m
1-3m
>3m
No sand patches
Time spent on plot (approx minutes)
Names of trackers (others add below)
Names of extra trackers
Organisation (eg Ranger Group)
Date
Thu 14 Mar., 2019
Time
17:14
Previous
Next
Finish

Appendix 3. Paper data form (for reference)

Department of Biodiversity, Conservation and Attractions

2HA SIGN PLOT DATASHEET v1.5
FOR OCCUPANCY SURVEYS

Grazing pressure

- ☐ High (lots of cow shit, tracks and damage
- ☐ Medium (some cows but not trashed)
- ☐ Low (not much sign of cows)

What percentage of the plot is suitable for tracking (eg sand or dirt)?

- ☐ To ¼ (0-25%)
- ☐ To ½ (25-50%)
- ☐ To ¾ (50-75%)
- ☐ Up to all (75-100%)

How big are the majority of the sand patches?

- ☐ less than 1m in width
- ☐ 1-3 m in width
- ☐ more than 3 m in width
- ☐ No sand patches

Shadow (look at own shadow

- ☐ Distinct shadow
- ☐ Slight shadow
- ☐ No shadow

Time since rain that would clear animal tracks (enter number) ☐ Days ☐ Weeks ☐ Months

Time since strong wind that would clear animal tracks (enter number) ☐ Days ☐ Weeks ☐ Months

Time since burnt (if known)

- ☐ <1 month
- ☐ <1 year
- ☐ >1 year

Any other comment/ notes:

Please submit datasheets to:
Department of Biodiversity, Conservation and Attractions - threatenedfauna@dbca.wa.gov.au, Woodvale Wildlife Research Centre, Bilby Research, Locked Bag 104 Bentley Delivery Centre WA 6983. (08) 9405 5105

Acknowledgements: WWF and Environs Kimberley assisted in producing the initial version of this template.

Department of Biodiversity, Conservation and Attractions

GOVERNMENT OF WESTERN AUSTRALIA

2HA SIGN PLOT DATASHEET v1.5
FOR OCCUPANCY SURVEYS

Species (add if not listed) All species prelisted	Tracks	Scats	Burrow	Digging	Digging into roots of plants	Tracks or sign on road	Other (eg sighting, remains, nest, resting place etc – add)	Juveniles present?	Age of most recent sign (1,2,3)
Bird - Emu									
Bird - Hopping									
Bird - Quail									
Bird - Turkey (Bustard)									
Bird - Walking									
Insect									
Other									
Cat									
Camel									
Cow									
Donkey									
Fox									
Goat									
Horse									
Pig									
Rabbit									

6. WHEN FINISHED WALKING RECORD THE FOLLOWING

Plot type

☐ Random ☐ Targeted at habitat ☐ Known location of target species

Plot sequence

☐ First time ☐ Repeat survey ☐ Unknown

Landform type

☐ Drainage line
☐ Salt lake system
☐ Plain (flat low ground)
☐ Dune or dunes
☐ Hill or higher area
☐ Other (type in below) ______________________

Soil type (substrate)

☐ Sand ☐ Soil/clay ☐ Gravel

Vegetation structure

☐ Shrubland ☐ Open woodland ☐ Dense woodland ☐ Open grassland

Vegetation thickness

☐ Open (easy to walk through) ☐ Thick (very hard to walk through)

Is there any green pick / seed or food plants regrowing after fire (ephemeral vegetation)?

☐ Yes ☐ No

If there are bilby diggings into roots what plants are they? ____

Department of Biodiversity, Conservation and Attractions

GOVERNMENT OF WESTERN AUSTRALIA

2HA SIGN PLOT DATASHEET v1.5

FOR OCCUPANCY SURVEYS

1. RECORD LOCATION AT THE START

Site Name/Location/Plot ID____

GPS:Lat/Easting____________________Long/Northing_____________________ Date ______/______/_____

Ranger group ____________________________________Time started__________Time finished__________

Team members____

2. TEAM SPLIT UP EVENLY AND WALK A 2HA AREA FOR APPROXIMATELY 20 MINUTES (Approximately 200m x 100m area)

3. INSPECT 100M OF THE ROAD FOR SIGN (ensure to tick "on road" for this sign)

4. RECORD ANIMAL DATA (tick boxes in table below ✓)

5. RECORD AGE OF SIGNS AT END OF WALKING 2 HA PLOT (1,2 or 3 in last column below)

Age of Sign: 1. Fresh 1-2 days old 2. Older, 3 days to 1 week 3. In hard mud/substrate or >1week

Species (add if not listed) All species prelisted	Tracks	Scats	Burrow	Digging	Digging into roots of plants	Tracks or sign on road	Other (eg sighting, remains, nest, resting place etc – add)	Juveniles present?	Age of most recent sign (1,2,3)
Bilby									
Bandicoot									
Bettong									
Dingo									
Echidna									
Euro									
Hopping mouse									
Kangaroo Red									
Kangaroo unknown									
Kangaroo W Grey									
Large rat									
Marsupial mole									
Mouse / Small Rodent / Dunnart									
Mulgara/Ampurta									
Possum									
Quoll									
Wallaby Agile									
Wallaby Hare									
Wallaby - Northern Nailtail									
Wallaby - Spectacled Hare									
Wallaby - unknown									
Lizard - Blue tongue									
Lizard - Goanna large									
Lizard - Goanna small									
Lizard - Great Desert Skink									
Lizard - Medium									
Lizard - Small									
Lizard - Thorny devil									
Sand slider (Lerista)									
Snake - other									
Snake - Python									
Bird - Curlew									

Department of Biodiversity, Conservation and Attractions

GOVERNMENT OF WESTERN AUSTRALIA

2HA SIGN PLOT DATASHEET v1.5
FOR OCCUPANCY SURVEYS

[OPTIONAL] If bilby burrows are found GPS the location of each one:

GPS Location (lat, long)	Any notes - location (e.g under log or tree), sensor camera number if placed

Photos of habitat taken? Y / N (if yes –list photo file names) ____

____

____

Appendix 4. Locations and survey occasions of 2 ha sign plots

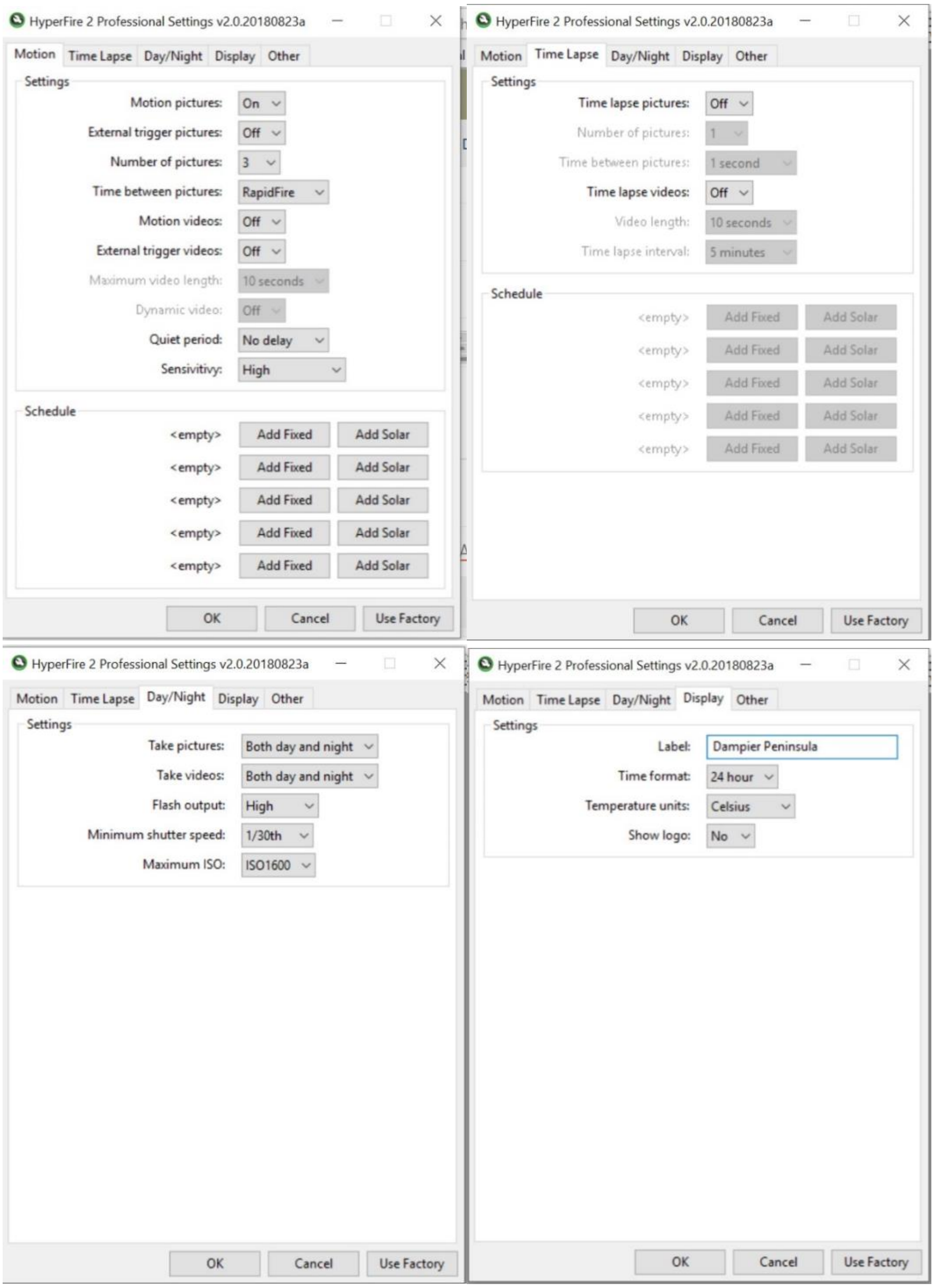
Plot ID	Latitude*	Longitude*	Occasion 1	Occasion 2	Occasion 3
B01	-17.966521	124.986539	18 Aug 2020	01 Sep 2020	14 Sep 2020
B02	-17.96663	125.021472	18 Aug 2020	01 Sep 2020	14 Sep 2020
B03	-17.966334	125.04711	18 Aug 2020	01 Sep 2020	14 Sep 2020
B04	-17.966062	125.072555	18 Aug 2020	01 Sep 2020	14 Sep 2020
B05	-17.959691	125.104898	18 Aug 2020	01 Sep 2020	17 Sep 2020
B06	-17.955666	125.133467	16 Jan 2015	01 Sep 2020	17 Sep 2020
B07	-17.963606	125.16215	18 Aug 2020	01 Sep 2020	17 Sep 2020
B08	-18.053302	125.369596	18 Aug 2020	01 Sep 2020	17 Sep 2020
B09	-18.09655	125.41303	18 Aug 2020	01 Sep 2020	17 Sep 2020
B10	-18.117238	125.44955	18 Aug 2020	01 Sep 2020	17 Sep 2020
B11	-18.172313	125.519367	19 Aug 2020	01 Sep 2020	14 Sep 2020
B12	-18.147066	125.504354	19 Aug 2020	01 Sep 2020	17 Sep 2020
Gooniyandi 01	-18.747149	126.1423	29 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 02	-18.744115	126.192701	29 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 03	-18.747935	126.222776	29 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 04	-18.755236	126.265632	29 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 05	-18.767133	126.313874	29 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 06	-18.776532	126.359493	29 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 07	-18.782651	126.403558	29 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 08	-18.779785	126.377826	29 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 09	-18.794576	126.511997	29 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 10	-18.788203	126.466481	29 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 11	-18.845404	126.510095	29 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 12	-18.743592	126.163531	30 Sep 2020	21 Oct 2020	17 Nov 2020
Gooniyandi 13	-18.766989	126.224117	30 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 14	-18.792894	126.244233	30 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 15	-18.811913	126.252494	30 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 16	-18.747431	126.195564	30 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 17	-18.987273	126.313207	02 Oct 2020	20 Oct 2020	16 Nov 2020
Gooniyandi 18	-18.879184	126.256158	30 Sep 2020	20 Oct 2020	17 Nov 2020
Gooniyandi 19	-18.962923	126.179387	30 Sep 2020	20 Oct 2020	16 Nov 2020
Gooniyandi 20	-18.945964	126.210247	30 Sep 2020	20 Oct 2020	16 Nov 2020
Gooniyandi 21	-19.006286	126.293872	02 Oct 2020	20 Oct 2020	16 Nov 2020
Gooniyandi 22	-19.007868	126.390348	02 Oct 2020	20 Oct 2020	16 Nov 2020
Kija01	-16.038518	128.412455	25 Aug 2020	08 Sep 2020	07 Oct 2020
Kija02	-16.12975	128.408408	26 Aug 2020	09 Sep 2020	22 Oct 2020
Kija03	-16.1319	128.444232	26 Aug 2020	10 Sep 2020	22 Oct 2020
Kija04	-16.13672	128.45777	26 Aug 2020	10 Sep 2020	22 Oct 2020
Kija05	-16.10804	128.430323	26 Aug 2020	10 Sep 2020	22 Oct 2020
Kija06	-16.084132	128.452434	26 Aug 2020	10 Sep 2020	22 Oct 2020
Kija07	-16.068678	128.474594	26 Aug 2020	10 Sep 2020	22 Oct 2020
Kija08	-16.042217	128.479475	26 Aug 2020	10 Sep 2020	22 Oct 2020
kija09	-16.277836	128.418277	27 Aug 2020	09 Sep 2020	06 Oct 2020
kija10	-16.254658	128.412729	27 Aug 2020	09 Sep 2020	06 Oct 2020
kija11	-16.224754	128.41234	27 Aug 2020	09 Sep 2020	00 Jan 1900
kija12	-16.223294	128.384672	27 Aug 2020	09 Sep 2020	06 Oct 2020
kija13	-16.212626	128.367006	27 Aug 2020	08 Sep 2020	07 Oct 2020

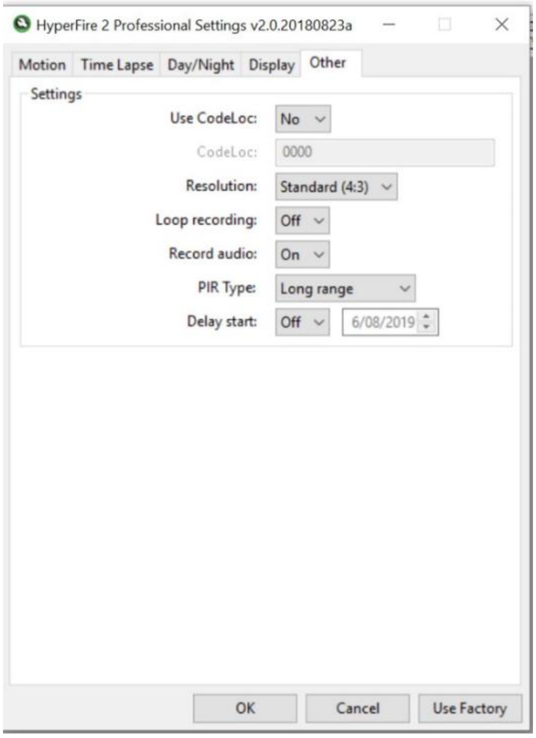
Plot ID	Latitude*	Longitude*	Occasion 1	Occasion 2	Occasion 3
NG01	-18.82348	125.584434	17 Aug 2020	05 Oct 2020	26 Oct 2020
NG02	-19.096538	125.720085	17 Aug 2020	05 Oct 2020	26 Oct 2020
NG03	-19.508091	125.533936	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG04	-19.502622	125.515636	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG05	-19.482043	125.493878	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG06	-19.462804	125.470003	18 Aug 2020	05 Oct 2020	26 Oct 2020
NG07	-19.383483	125.614406	18 Aug 2020	06 Oct 2020	28 Oct 2020
NG08	-19.384257	125.63353	18 Aug 2020	06 Oct 2020	28 Oct 2020
NG09	-19.386225	125.728098	18 Aug 2020	06 Oct 2020	28 Oct 2020
NG10	-19.384853	125.660114	00 Jan 1900	06 Oct 2020	28 Oct 2020
NG11	-19.49486	125.495122	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG12	-19.501785	125.504451	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG13	-19.517429	125.533019	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG14	-19.526128	125.541698	18 Aug 2020	06 Oct 2020	27 Oct 2020
NG15	-19.503581	125.432767	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG16	-19.511068	125.425247	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG17	-19.542056	125.399951	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG18	-19.548433	125.394588	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG19	-19.569975	125.376296	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG20	-19.580952	125.366925	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG21	-19.595676	125.356428	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG22	-19.608829	125.342616	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG23	-19.499562	125.42492	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG24	-19.498414	125.402427	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG25	-19.4929	125.364243	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG26	-19.491929	125.346275	19 Aug 2020	07 Oct 2020	27 Oct 2020
NG27	-19.394899	125.524382	20 Aug 2020	05 Oct 2020	26 Oct 2020
NG28	-19.362639	125.551851	20 Aug 2020	05 Oct 2020	26 Oct 2020
NG29	-19.339482	125.570956	20 Aug 2020	05 Oct 2020	26 Oct 2020
NG30	-19.307429	125.598329	20 Aug 2020	05 Oct 2020	26 Oct 2020
NM01	-18.298182	123.756349	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM02	-18.311865	123.795107	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM03	-18.333287	123.853517	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM04	-18.339693	123.871042	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM05	-18.344029	123.882851	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM06	-18.348706	123.895478	01 Sep 2020	15 Sep 2020	15 Sep 2020
NM07	-18.337654	123.91385	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM08	-18.415995	123.933836	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM09	-18.422364	123.949071	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM10	-18.426543	123.96112	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM11	-18.437756	123.985639	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM12	-18.451316	124.019278	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM13	-18.468966	124.060582	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM14	-18.338091	123.913146	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM15	-18.328255	123.929602	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM16	-18.24821	124.085997	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM17	-18.25955	124.062474	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM18	-18.282095	124.011485	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM19	-18.301386	123.976638	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM20	-18.298794	123.851424	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM21	-18.28514	123.722076	02 Sep 2020	15 Sep 2020	20 Oct 2020

Plot ID	Latitude*	Longitude*	Occasion 1	Occasion 2	Occasion 3
NM21	-18.285202	123.722173	00 Jan 1900	00 Jan 1900	20 Oct 2020
NM22	-18.270324	123.690266	01 Sep 2020	15 Sep 2020	20 Oct 2020
NM23	-18.053143	123.537922	02 Sep 2020	15 Sep 2020	20 Oct 2020
NM24	-17.897806	123.605317	02 Sep 2020	16 Sep 2020	20 Oct 2020
NM25	-17.903274	123.624546	02 Sep 2020	16 Sep 2020	20 Oct 2020
NM26	-17.902989	123.664172	02 Sep 2020	16 Sep 2020	20 Oct 2020
NM27	-17.929837	123.691439	02 Sep 2020	16 Sep 2020	20 Oct 2020
NM28	-18.795069	124.500986	01 Sep 2020	14 Sep 2020	28 Oct 2020
NM29	-18.822724	124.493207	01 Sep 2020	14 Sep 2020	28 Oct 2020
NM30	-18.869731	124.482026	01 Sep 2020	14 Sep 2020	28 Oct 2020
NM31	-18.778575	124.499067	03 Sep 2020	15 Sep 2020	28 Oct 2020

*WGS 84

Appendix 5. Settings for Reconyx 2 Hyperfire cameras




HyperFire 2 Professional Settings v2.0.20180823a
Motion
Time Lapse
Day/Night
Display
Other
Settings
Use CodeLoc:
No
CodeLoc:
0000
Resolution:
Standard (4:3)
Loop recording:
Off
Record audio:
On
PIR Type:
Long range
Delay start:
Off
6/08/2019
OK
Cancel
Use Factory

Appendix 6. Predator occupancy and detection at bilby populations captured by remote cameras

Population and species	Model	**Probability of occupancy**	SE	Lower 95% CI	Upper 95% CI	Beta	SE beta	**Probability of detection**	SE	Lower 95% CI	Upper 95% CI	Beta	SE beta	N
Yarri Yarri (Nyikina Mangala)														
Cat														
All cameras	psi(.)p(.)	**0.67**	0.19	0.27	0.92	0.71	0.87	**0.53**	0.10	0.35	0.71	0.13	0.39	6
Cameras on tracks	psi(.)p(On_tracks)	**0.67**	0.19	0.27	0.92	0.70	0.87	**0.52**	0.11	0.32	0.72	0.26	0.80	3
Cameras on burrows								**0.56**	0.20	0.21	0.86	-0.17	0.91	3
Fox														
All cameras	psi(.)p(.)	**0.51**	0.40	0.04	0.96	0.05	1.60	**0.14**	0.12	0.02	0.53	-1.82	1.00	6
Cameras on tracks	psi(.)p(On_tracks)	**0.50**	0.34	0.06	0.94	0.00	1.37	**0.22**	0.20	0.03	0.73	-2.39	1.25	3
Cameras on burrows								**0.08**	0.10	0.01	0.51	1.12	1.54	3
Dingo														
All cameras	psi(.)p(.)	**0.39**	0.24	0.08	0.82	-0.46	1.00	**0.25**	0.13	0.07	0.57	-1.12	0.72	6
Cameras on tracks	psi(.)p(On_tracks)	**0.77**	0.35	0.06	0.99	1.23	1.99	**0.25**	0.13	0.07	0.57	-32.47	NA	3
Cameras on burrows								**0.00**	NA	NA	NA	31.35	NA	3
Kurlku (Ngurrara)														
Cat														
All cameras	psi(.)p(.)	**0.68**	0.20	0.27	0.92	0.74	0.89	**0.46**	0.10	0.28	0.65	-0.17	0.39	6

Cameras on tracks	psi(.)p(On_tracks)	**0.68**	0.20	0.27	0.92	0.74	0.90	**0.42**	0.14	0.19	0.69	-0.02	0.55	3
Cameras on burrows								**0.50**	0.14	0.25	0.74	-0.31	0.79	3
Bawoorrooga (Gooniyandi)														
Cat														
All cameras	psi(.)p(.)	**1**	-	-	-	-	-	**0.32**	0.06	0.21	0.44	-0.77	0.28	6
Cameras on tracks	psi(.)p(On_tracks)	**1**	-	-	-	-	-	**0.23**	0.08	0.12	0.41	-0.41	0.37	3
Cameras on burrows								**0.40**	0.09	0.24	0.58	-0.78	0.57	3
Fox														
All cameras	psi(.)p(.)	**0.20**	0.19	0.02	0.72	-1.40	1.20	**0.17**	0.14	0.03	0.58	-1.60	0.99	6
Cameras on tracks								**0**	-	-	-	-1.60	0.99	3
Cameras on burrows	psi(.)p(On_tracks)	**0.40**	0.35	0.04	0.92	-0.42	1.45	**0.17**	0.14	0.03	0.58	-28.06	-	3
All sites combined														
Cat														
All cameras	psi(.)p(.)	**0.80**	0.10	0.54	0.93	1.40	0.64	**0.39**	0.05	0.31	0.49	-0.43	0.20	18
Cameras on tracks	psi(.)p(On_tracks)							**0.36**	0.06	0.25	0.49	-0.24	0.30	9
Cameras on burrows		**0.80**	0.10	0.54	0.93	1.36	0.62	**0.44**	0.07	0.30	0.59	-0.32	0.40	9
Fox														
All cameras	psi(.)p(.)	**0.23**	0.14	0.06	0.58	-1.22	0.79	**0.15**	0.09	0.04	0.42	-1.71	0.70	18
Cameras on tracks	psi(.)p(On_tracks)	**0.21**	0.13	0.06	0.55		0.76	**0.21**	0.21	0.02	0.76	-1.80	0.74	9

Cameras on burrows						-1.30		**0.14**	0.09	0.04	0.41	0.48	1.40	9
Dingo														
All cameras	psi(.)p(.)	**0.12**	0.08	0.03	0.39	-1.96	0.78	**0.26**	0.13	0.08	0.57	-1.07	0.70	18
Cameras on tracks	psi(.)p(On_tracks)							**0.26**	0.13	0.08	0.57	-52.56	-	9
Cameras on burrows		**0.25**	0.16	0.06	0.63	-1.12	0.85	**0**	-	-	-	51.49	-	9

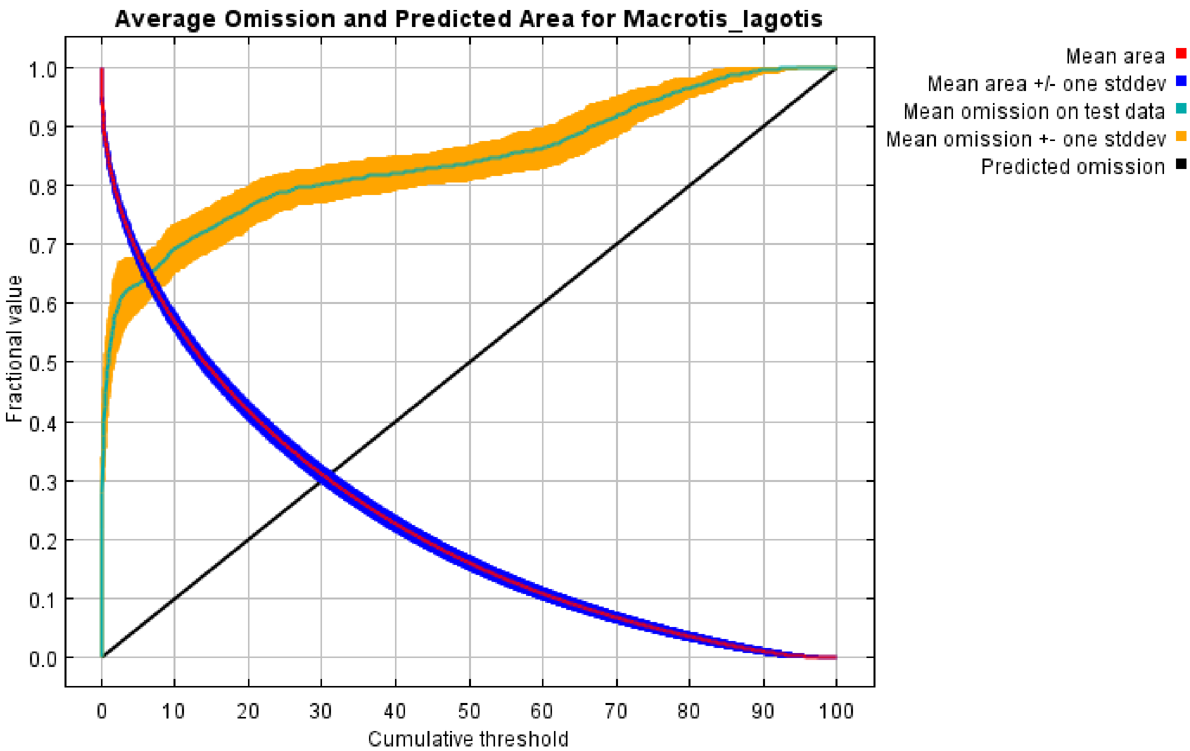
Appendix 7. Maxent output including vegetation type

Replicated Maxent model for Macrotis_lagotis

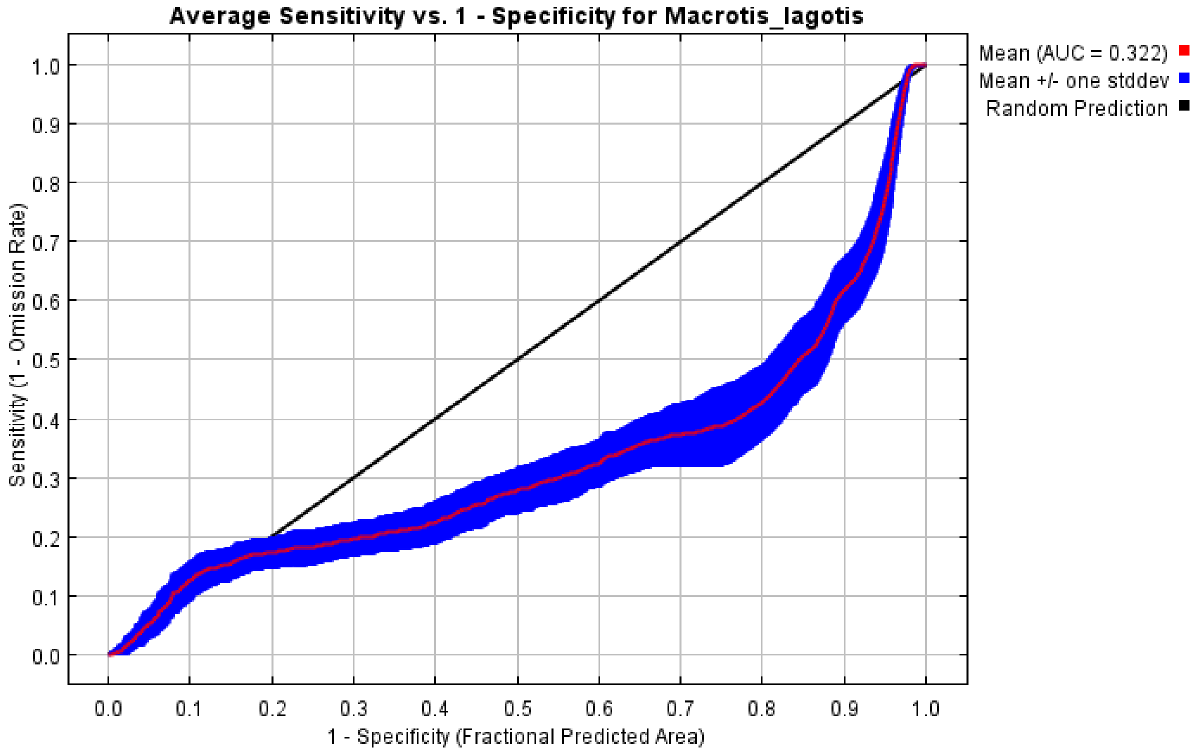
This page summarises the results of 15 split-sample models for Macrotis_lagotis, created Thu Jul 08 02:59:56 AWST 2021 using Maxent version 3.4.4.

Analysis of omission/commission

The following picture shows the test omission rate and predicted area as a function of the cumulative threshold, averaged over the replicate runs. The omission rate should be close to the predicted omission, because of the definition of the cumulative threshold.

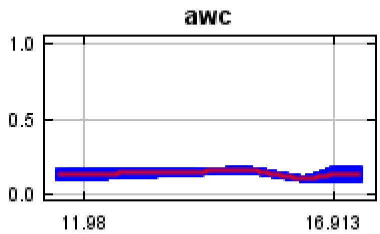


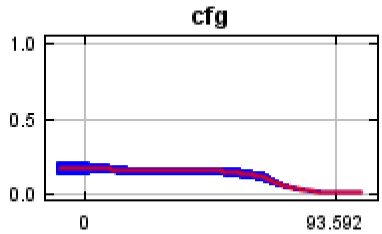
The next picture is the receiver operating characteristic (ROC) curve for the same data, again averaged over the replicate runs. Note that the specificity is defined using predicted area, rather than true commission (see the paper by Phillips, Anderson and Schapire cited on the help page for discussion of what this means). The average test AUC for the replicate runs is 0.322, and the standard deviation is 0.032.

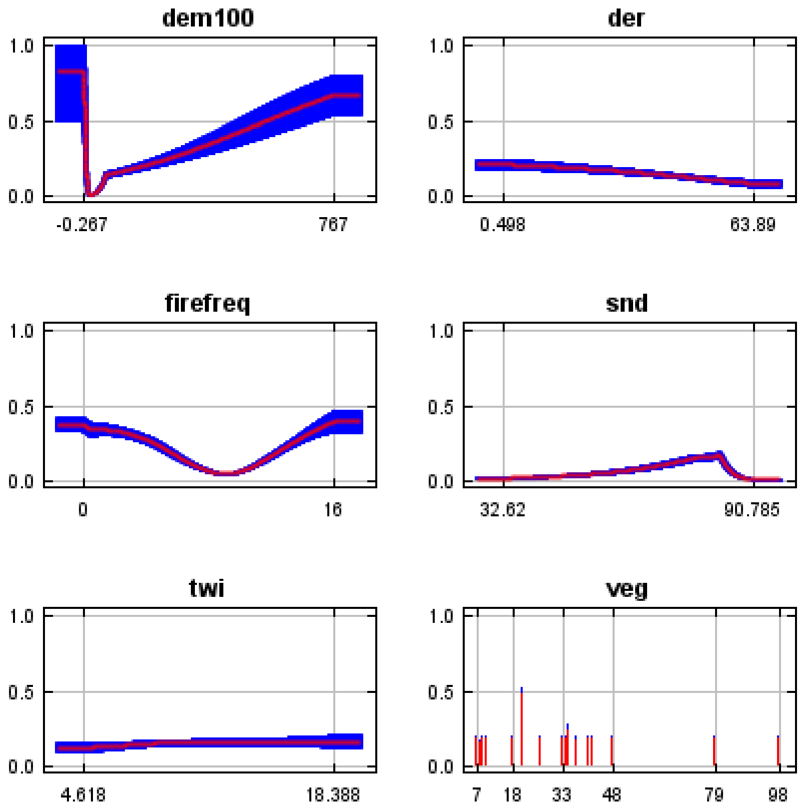


Response curves

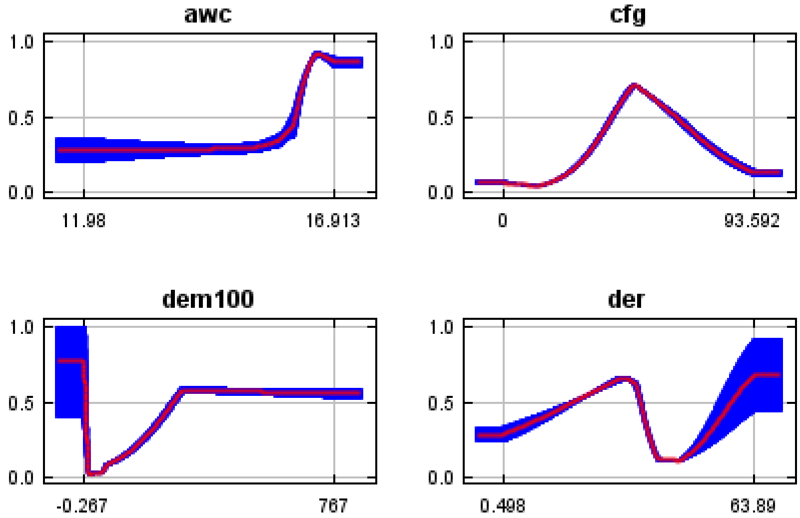
These curves show how each environmental variable affects the Maxent prediction. The curves show how the predicted probability of presence changes as each environmental variable is varied, keeping all other environmental variables at their average sample value. Click on a response curve to see a larger version. Note that the curves can be hard to interpret if you have strongly correlated variables, as the model may depend on the correlations in ways that are not evident in the curves. In other words, the curves show the marginal effect of changing exactly one variable, whereas the model may take advantage of sets of variables changing together. The curves show the mean response of the 15 replicate Maxent runs (red) and and the mean +/- one standard deviation (blue, two shades for categorical variables).

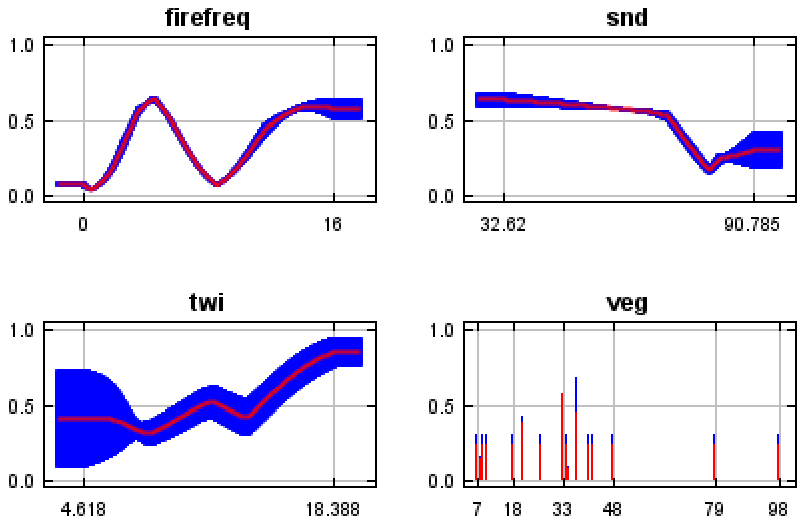






In contrast to the above marginal response curves, each of the following curves represents a different model, namely, a Maxent model created using only the corresponding variable. These plots reflect the dependence of predicted suitability both on the selected variable and on dependencies induced by correlations between the selected variable and other variables. They may be easier to interpret if there are strong correlations between variables.



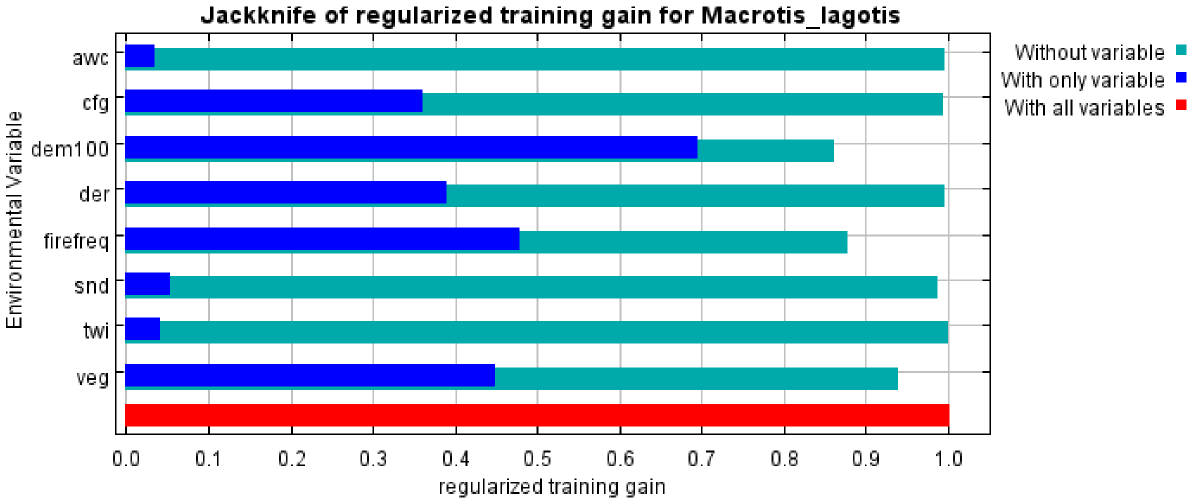


Analysis of variable contributions

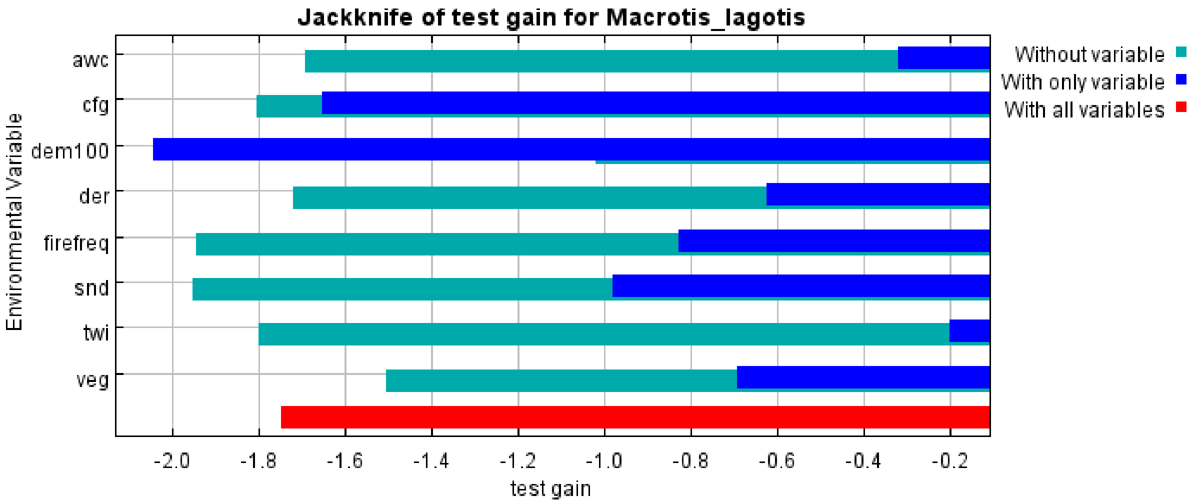
The following table gives estimates of relative contributions of the environmental variables to the Maxent model. To determine the first estimate, in each iteration of the training algorithm, the increase in regularised gain is added to the contribution of the corresponding variable, or subtracted from it if the change to the absolute value of lambda is negative. For the second estimate, for each environmental variable in turn, the values of that variable on training presence and background data are randomly permuted. The model is reevaluated on the permuted data, and the resulting drop in training AUC is shown in the table, normalized to percentages. As with the variable jackknife, variable contributions should be interpreted with caution when the predictor variables are correlated. Values shown are averages over replicate runs.

Variable	Percent contribution	Permutation importance
dem100	41.9	0
veg	40.8	0
firefreq	11.9	0
der	1.6	1.4
snd	1.5	95.6
cfg	1.4	0.9
awc	0.8	1
twi	0.1	1.1

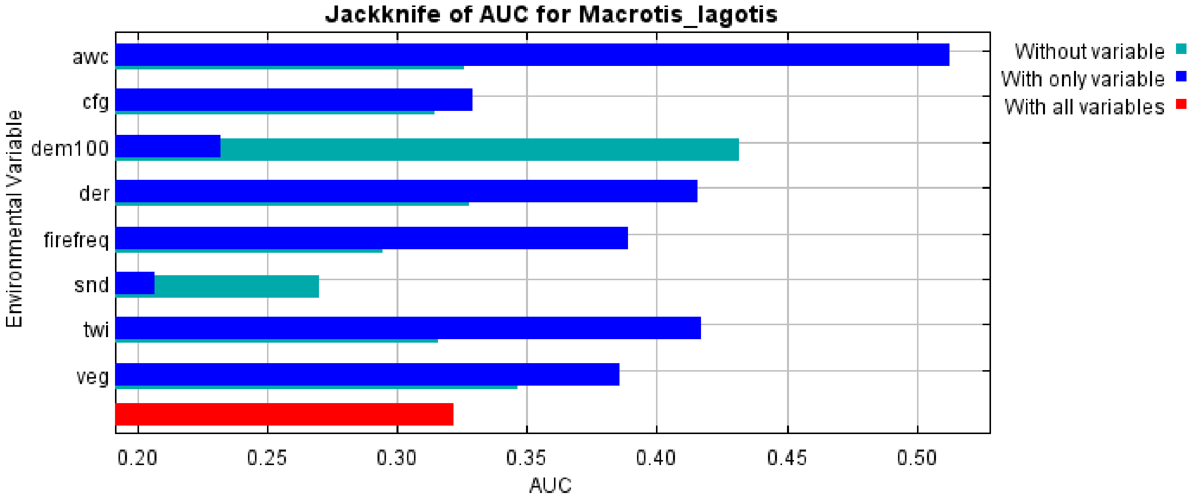
The following picture shows the results of the jackknife test of variable importance. The environmental variable with highest gain when used in isolation is dem100, which therefore appears to have the most useful information by itself. The environmental variable that decreases the gain the most when it is omitted is dem100, which therefore appears to have the most information that is not present in the other variables. Values shown are averages over replicate runs.



The next picture shows the same jackknife test, using test gain instead of training gain. Note that conclusions about which variables are most important can change, now that we are looking at test data.



Lastly, we have the same jackknife test, using AUC on test data.



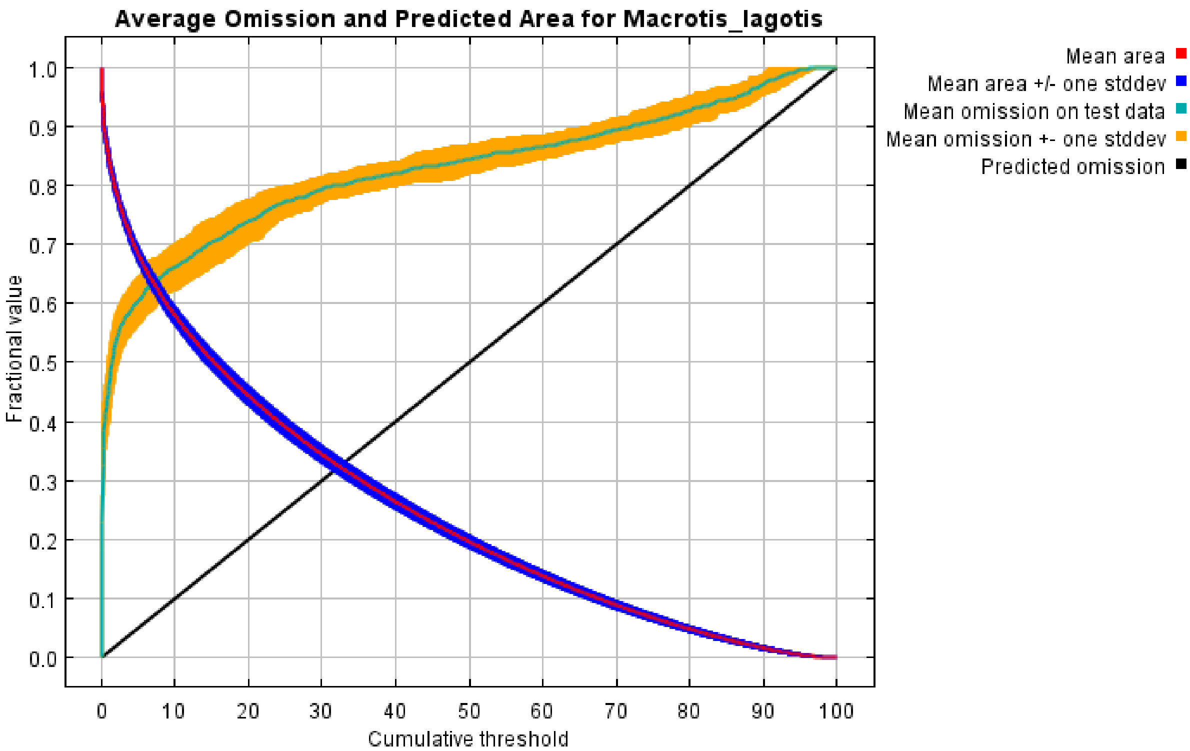
Appendix 8. Maxent output excluding vegetation type

Replicated Maxent model for Macrotis_lagotis

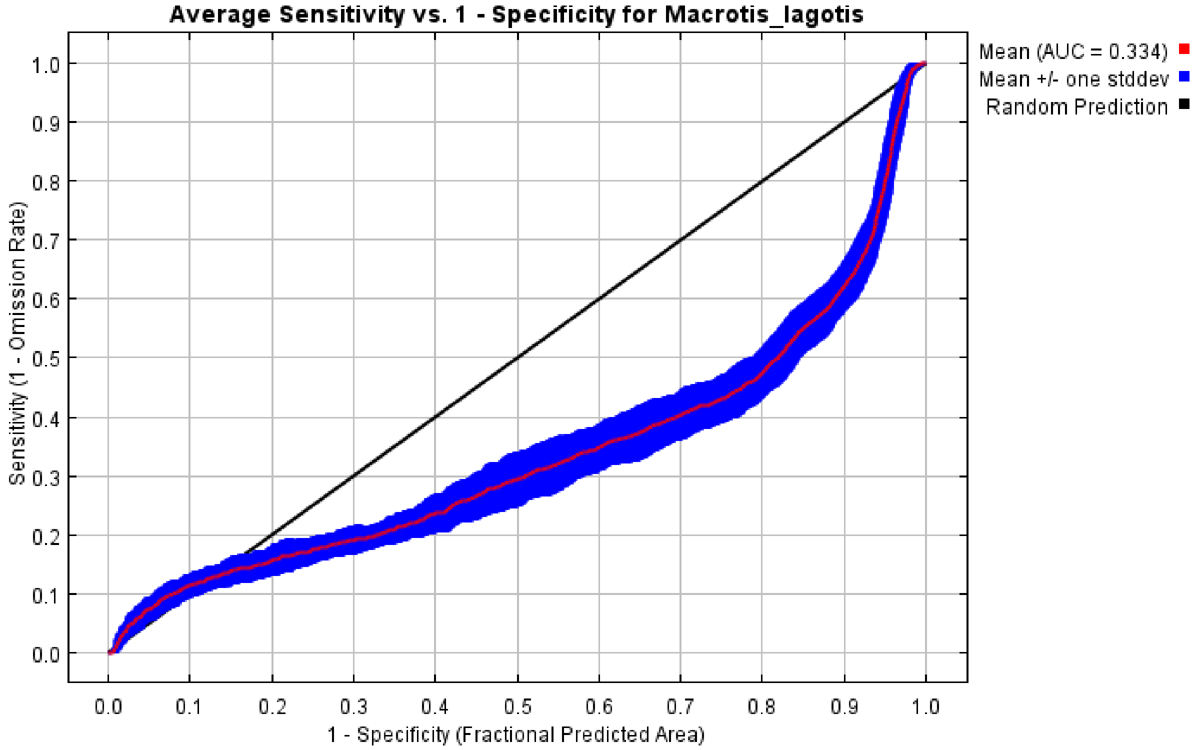
This page summarises the results of 15 split-sample models for Macrotis_lagotis, created Thu Jul 08 03:55:06 AWST 2021 using Maxent version 3.4.4.

Analysis of omission/commission

The following picture shows the test omission rate and predicted area as a function of the cumulative threshold, averaged over the replicate runs. The omission rate should be close to the predicted omission, because of the definition of the cumulative threshold.

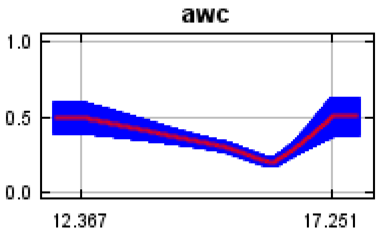


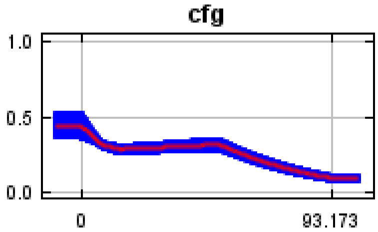
The next picture is the receiver operating characteristic (ROC) curve for the same data, again averaged over the replicate runs. Note that the specificity is defined using predicted area, rather than true commission (see the paper by Phillips, Anderson and Schapire cited on the help page for discussion of what this means). The average test AUC for the replicate runs is 0.334, and the standard deviation is 0.027.

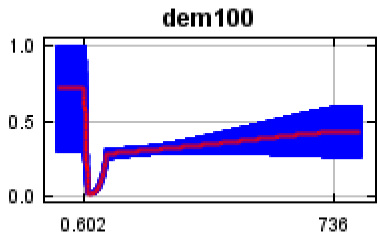


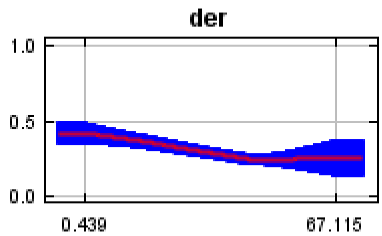
Response curves

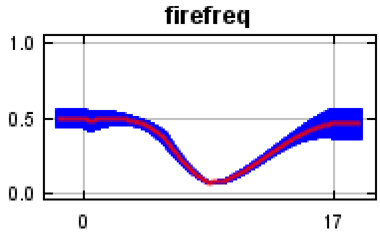
These curves show how each environmental variable affects the Maxent prediction. The curves show how the predicted probability of presence changes as each environmental variable is varied, keeping all other environmental variables at their average sample value. Click on a response curve to see a larger version. Note that the curves can be hard to interpret if you have strongly correlated variables, as the model may depend on the correlations in ways that are not evident in the curves. In other words, the curves show the marginal effect of changing exactly one variable, whereas the model may take advantage of sets of variables changing together. The curves show the mean response of the 15 replicate Maxent runs (red) and and the mean +/- one standard deviation (blue, two shades for categorical variables).

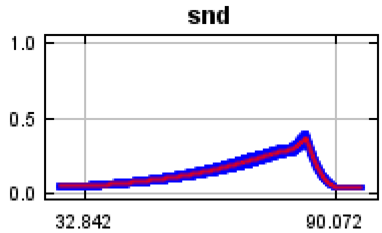


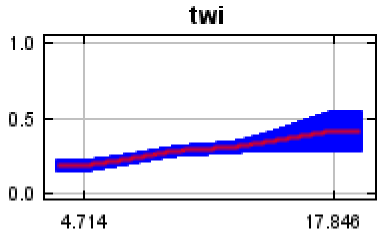




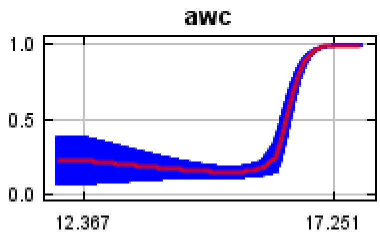


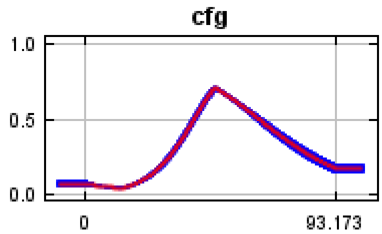


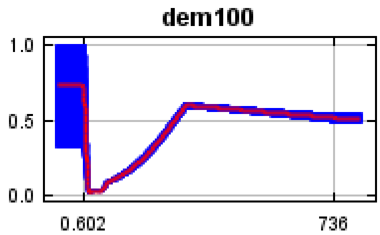


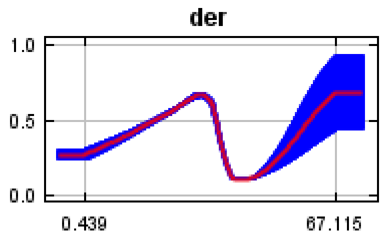


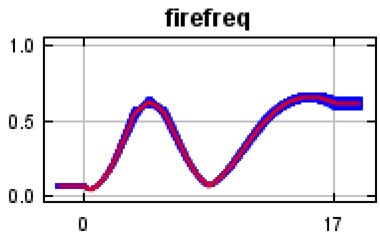
In contrast to the above marginal response curves, each of the following curves represents a different model, namely, a Maxent model created using only the corresponding variable. These plots reflect the dependence of predicted suitability both on the selected variable and on dependencies induced by correlations between the selected variable and other variables. They may be easier to interpret if there are strong correlations between variables.

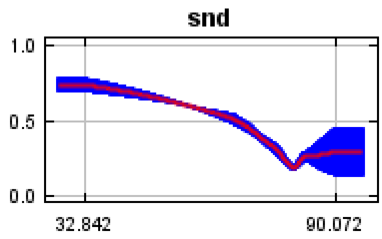


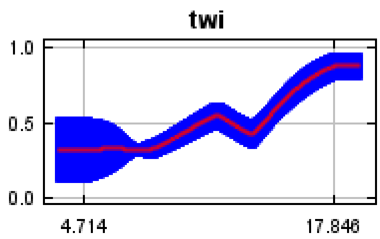










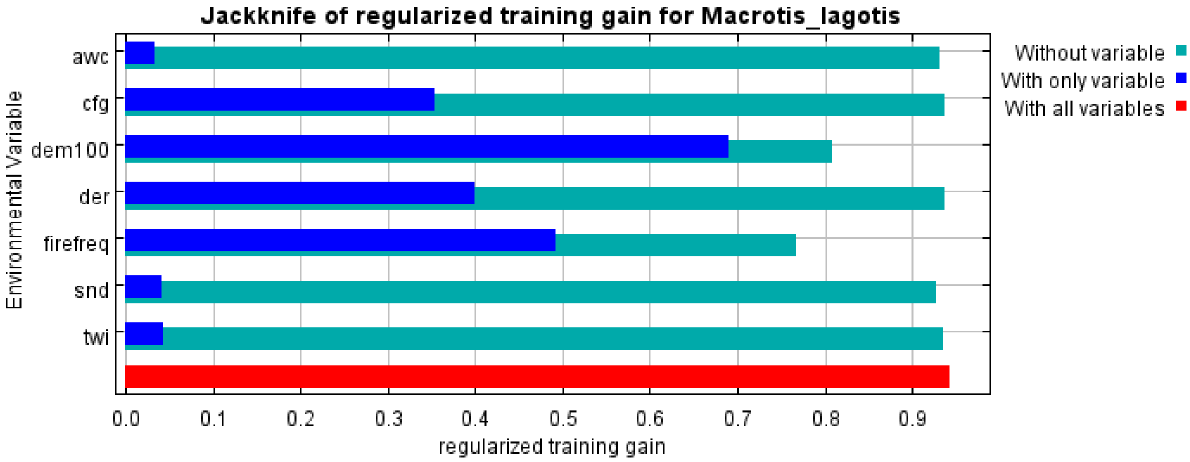


Analysis of variable contributions

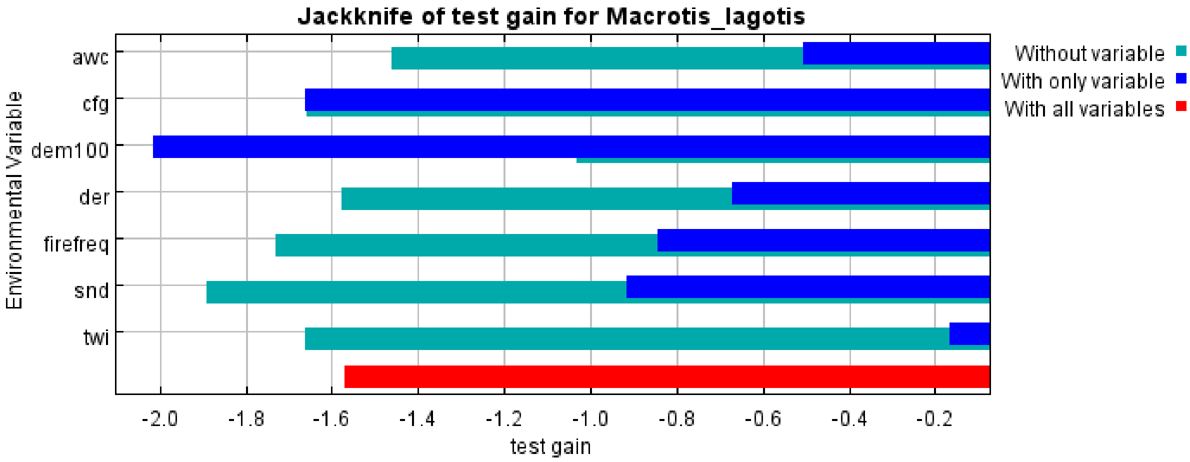
The following table gives estimates of relative contributions of the environmental variables to the Maxent model. To determine the first estimate, in each iteration of the training algorithm, the increase in regularised gain is added to the contribution of the corresponding variable, or subtracted from it if the change to the absolute value of lambda is negative. For the second estimate, for each environmental variable in turn, the values of that variable on training presence and background data are randomly permuted. The model is reevaluated on the permuted data, and the resulting drop in training AUC is shown in the table, normalized to percentages. As with the variable jackknife, variable contributions should be interpreted with caution when the predictor variables are correlated. Values shown are averages over replicate runs.

Variable	Percent contribution	Permutation importance
dem100	72.9	0
firefreq	16.7	0
der	2.8	0
snd	2.3	97.3
cfg	2.3	1.6
awc	1.8	1.1
twi	1.1	0

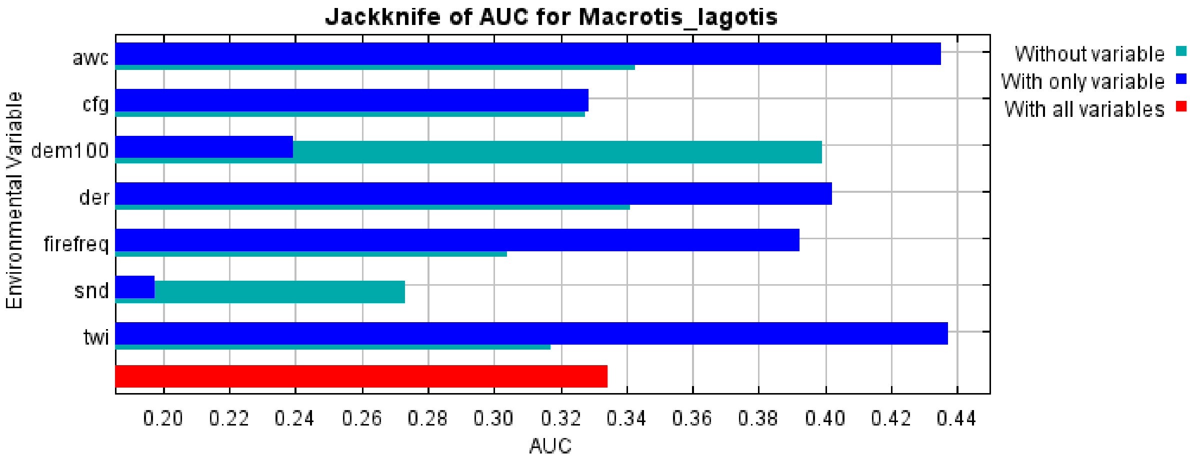
The following picture shows the results of the jackknife test of variable importance. The environmental variable with highest gain when used in isolation is dem100, which therefore appears to have the most useful information by itself. The environmental variable that decreases the gain the most when it is omitted is firefreq, which therefore appears to have the most information that is not present in the other variables. Values shown are averages over replicate runs.



The next picture shows the same jackknife test, using test gain instead of training gain. Note that conclusions about which variables are most important can change, now that we are looking at test data.



Lastly, we have the same jackknife test, using AUC on test data.



Appendix 9. A quick guide to distinguishing dingo/dog, fox and cat tracks

Avisual representation of the differences in dingo/dog, fox and cat tracks is provided below. For further details see Moseby et al. (2009).