Assessment of trends in Southern Brown Bandicoot occupancy in the southern forests of New South Wales (2009-2019)

Leroy Gonsalves and Brad Law

DPI Forest Science

13th May 2021, revised 26th May 2021

Introduction

Camera trapping surveys for the Southern Brown Bandicoot (SBB; *Isoodon obesulus*) in the Eden forests have been undertaken by *Forestry Corporation of NSW* over a 11-year period and are ongoing as part of monitoring specified in an associated species management plan.

DPI Forest Science was requested to process camera trap data from the above monitoring program and undertake trend analysis to assess occupancy of the SBB. As part of the analysis, the influence of potential climatic (annual rainfall), biotic (activity of predators) and disturbance (fire and harvesting) variables on dynamic processes (colonisation and extinction) that influence the meta-population was assessed. Based on the outcomes of the analysis, recommendations to improve the ongoing monitoring and management of the species are provided.

Methods

Study area

The study was carried out in East Boyd, Nadgee, Timbillica and Yambulla State Forests south of Eden (Fig. 1.). A total of 40 monitoring sites were established as part of a Species Management Plan, which was developed to assess the effectiveness of prescription measures aimed at minimising impacts of harvesting on the SBB, which included excluding assumed suitable habitat (primarily Yertchuk *Eucalyptus consideniana* and shrub dominated forest communities) from harvesting. Twenty monitoring sites were established within or nearby to this habitat type, while 20 sites were within other forest types. Fox baiting was carried-out in the area sporadically on a rotating panel prior to 2008 (initially for livestock protection), but from 2008-2018 it was continuous, on average every 6-8 weeks. Regular baiting has lapsed since 2018 due to staffing issues.

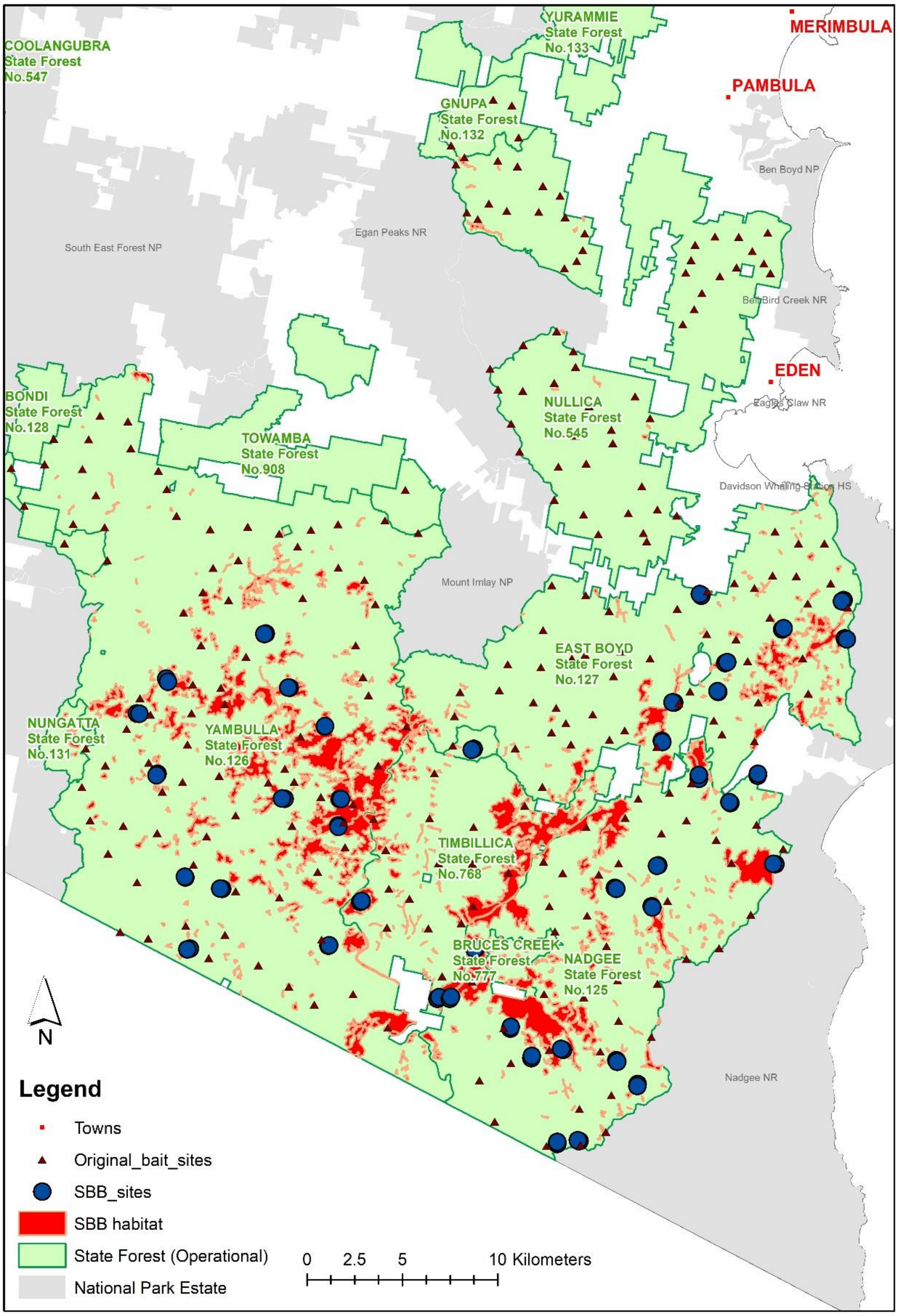


Fig.1. Map of study area with camera monitoring sites, SBB habitat (Yertchuk and shrub dominated forest communities) and predator baiting sites.

Camera trapping and processing

In all, 40 sites were sampled among years (Table 1), with each site sampled using two cameras, one Infrared camera (Scoutguard SG550) and one white-flash (Scoutguard SG560) deployed ~100m apart. The use of two cameras with a similar spacing has been suggested in pilot assessments of detectability for the species in the Grampians, Victoria (Stevens et al. 2010). The Scoutguard SG550 was programmed to take three consecutive images per trigger, whereas the Scoutguard SG560 took a single image, with both cameras having a quiet period of 5 minutes between triggers. The cameras were tied to a tree at approximately 50-75cm height and angled towards a lure (truffle oil within a tea-strainer or vent cowling pegged into the ground) approximately 1.5m from the camera. The vegetation around the lure was cleared to bare earth at each camera deployment.

Images obtained from 11-years (2009-2019) of sampling were identified and tagged in ExifPro V2.1 using available keys and reference material (Fig. 2a-2d). Tagged images were exported as a .csv file with metadata (including date and timestamp) and site details for each image.

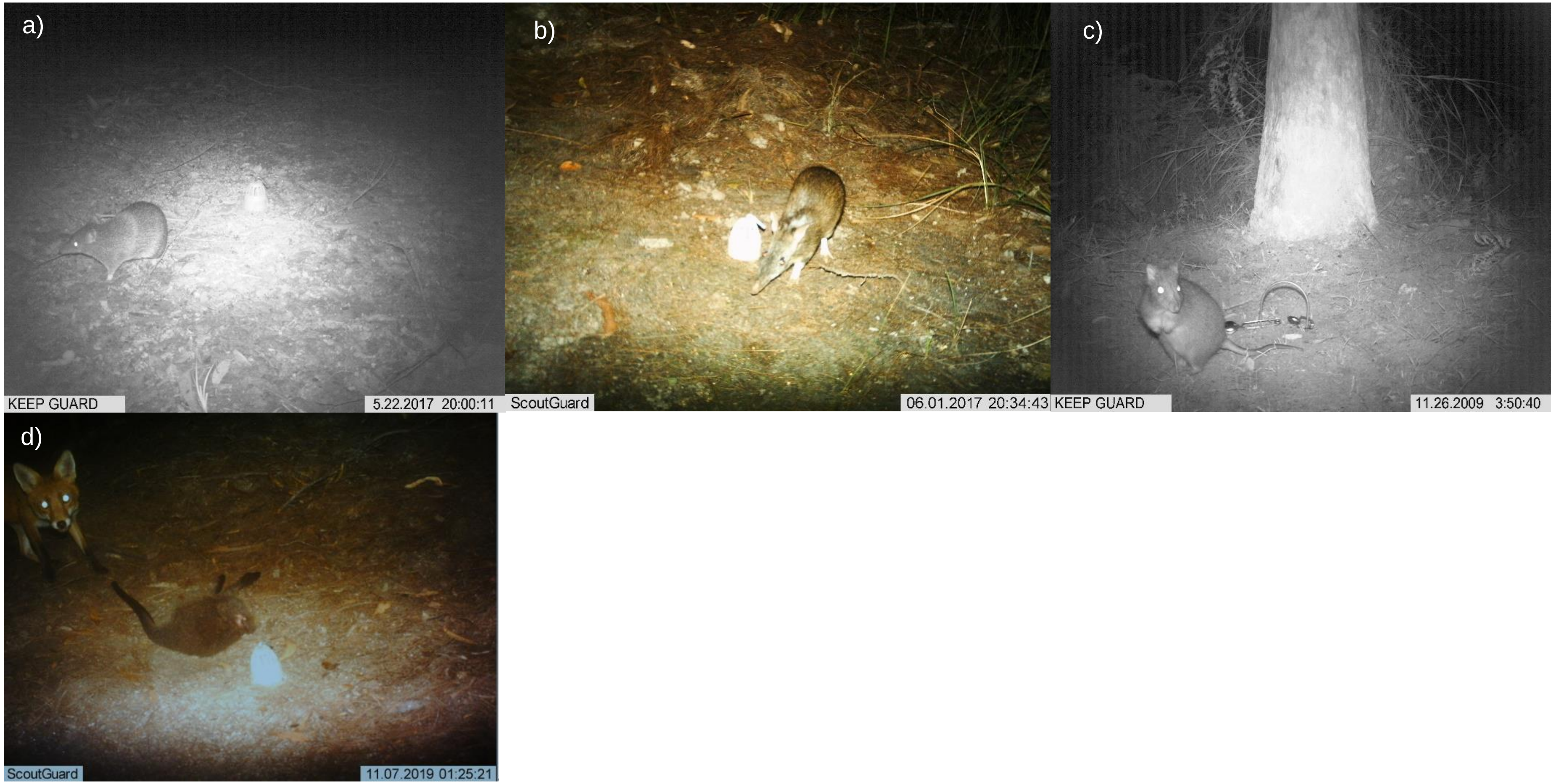


Fig. 2. Examples of images that were collected during the monitoring program: a) Southern Brown Bandicoot, b) Long-nosed Bandicoot and c) Long-nosed Potoroo and d) Red Fox with swamp wallaby carcass.

Occupancy modelling

A dynamic occupancy modelling framework was used to estimate SBB occupancy in the Eden forests between 2009 and 2019 based on detections using passive infrared cameras. We considered this approach to be superior to modelling changes in bandicoot activity because occupancy modelling accounts for imperfect detection, even though the number of sites available was relatively low. Sampling was undertaken for at least two weeks in multiple seasons following the initial survey in 2009 (spring only). For the first few years sampling occurred 3-4 times a year, but regular sampling was undertaken in spring and autumn in subsequent years. As such, analyses focused on just these two seasons while data for 2009 and 2010 were pooled to provide more data from which to build relationships for initial occupancy. Since two cameras separated by~100m were used at each site, we considered these were not independent which is a violation of the assumption of independence of 'sites' (cameras) for the analysis. To account for this potential, data from both cameras were pooled and the analysis was undertaken at the site-level rather than at the level of the camera.

A detection history matrix was generated such that each sampling day (9am-9am to match local rainfall data) was assigned with a "1" if a SBB was detected and a "0" if not detected. The detection history matrix was restricted to a 14-day sampling window in each season (spring and autumn) to standardise the sampling effort among sites. For sites where both cameras did not sample on a given night (e.g., camera trap failure), the sampling day was assigned as missing data ("NA"). For sites where only one camera did not sample, data from the other operating camera was used to designate the detection history. Unbalanced sampling effort (i.e., one camera vs two cameras) per site was accounted for when modelling detection probability (see below).

Table 1. Summary of sampling effort (at least one operational camera) by season among years.

Year of survey	Number of sites (autumn)	Number of sites (spring)	Naïve Occupancy of SBB
2009	0	39	0.08
2010	40	40	0.25
2011	37	39	0.33
2012	37	40	0.33
2013	40	40	0.55
2014	38	37	0.35
2015	40	40	0.38
2016	40	40	0.15
2017	40	40	0.18
2018	40	40	0.18
2019	40	31	0.10

A hierarchical approach was taken to modelling in order to reduce the total number of candidate models. We first modelled detection probability to account for imperfect detection associated with surveys and held initial occupancy, colonisation and extinction constant. Detection probability was allowed to vary with season of survey, camera trapping effort (1 or 2 cameras) or held constant (null model) among all 'visits' (sampling days) to a site. The top model was carried forward to model initial occupancy (i.e., occupancy in 2009).

Initial occupancy was modelled while holding colonisation and extinction constant, which is the standard approach used for dynamic occupancy modelling. Several site-based variables were included as covariates for occupancy – forest type extent within 200 m buffer of each site (messmate yellow stringybark communities, silvertop ash communities, stringybark coastal, woollybutt mixed coastal eucalypt communities, yertchuk communities), topographic position index (raw and stretched), elevation (midpoint between cameras), extent of SBB habitat exclusion within 200 m buffer of each site, LiDAR-derived metrics for cover using several height bins (2 m) in a 0-15 m vertical profile as well as canopy cover and average canopy height, extent of four fire age classes (<5 years, 5-15 years, >15-30 years and >30 years) within a 200 m buffer of each site, extent of four harvesting age classes (<5 years, 5-15 years, >15-30 years and >30 years) within a 200 m buffer of each site and annual rainfall preceding the year of sampling (Table 2). A 200 m buffer was used to encompass local heterogeneity surrounding the two cameras used at each site. The three age classes were based on the presence of open vegetation structure soon after harvesting or fire disturbance, and then gradual thickening from regeneration followed by gradual opening 30 years after disturbance. Fire extent included by both, hazard reduction and wildfire, with records for the latter available from 1992, whereas wildfire data was available prior to this. A null model that held initial occupancy constant across sites was also included in the set of candidate models.

The influence (direction and magnitude) of a supported covariate was assessed by plotting occupancy estimates that were generated while holding all other supported covariates at the median value.

Colonisation (proportion of unoccupied sites where the species was detected in the following season) and extinction (proportion of occupied sites where the species was not detected in the following season) parameters were then modelled using the top model for initial occupancy. Variables included as covariates for these parameters were extent of four fire age classes (<5 years, 5-15 years, >15-30 years and >30 years), extent of four harvesting age classes (<5 years, 5-15 years, >15-30 years and >30 years), annual rainfall preceding the year of sampling number and cat activity (no. of images of *Felis catus* standardised for sampling effort per site). Foxes were not included because they had a low occurrence in the study area (mean±se = 3±1 images per year Vs mean = 46 images per year for cats; Table 4). A null model where these parameters were held constant was also included.

Prior to analysis, covariates were examined for collinearity. None of the covariates considered were highly correlated (r>0.7).

Table 2. Summary statistics (minimum, maximum and mean) for covariates used in modelling of occupancy. A 200 m buffer around the mid-point of cameras defined the extent for environmental variables.

Covariate	Min	Max	Mean
Topographic Position Index (TPI)	-10.0	24.7	1.0
TPI (stretched)	85.0	231.0	131.1
Elevation (m ASL)	25.0	420.0	175.9
Extent (%) of SBB habitat exclusion	0	100	9.0
Annual rainfall preceding year of survey	401.6	1183.4	862.6
Extent (%) of Messmate/Yellow Stringybark communities	0	75.9	16.1
Extent (%) of non-forest, she-oak, scrub, rainforest	0	54.0	5.9
Extent (%) of silvertop ash communities	0	98.4	37.8
Extent (%) of stringybark/coastal	0	68.2	13.0
Extent (%) of woollybutt/mixed coastal eucalypt	0	24.1	1.0
Extent (%) yertchuk communities	0	100.0	24.1
Extent (%) of recent fire (<5 years)	0	0.010	0.001
Extent (%) of intermediate fire (5-15 years)	0	0.010	0.003
Extent (%) of old fire (>15-30 years)	0	0.010	0.003
Extent (%) of long unburnt (>30 years)	0	0.010	0.002
Extent (%) of recent harvesting* (<5 years)	0	42.0	1.4
Extent (%) of intermediate harvesting* (5-15 years)	0	70.9	4.0
Extent (%) of old harvesting* (>15-30 years)	0	98.3	14.1
Extent (%) of long undisturbed (>30 years)	0	100.0	43.1
Extent (%) of unlogged	1	100.0	37.8
Extent (%) of recent thinning (<5 years)	0	98.8	6.0
Extent (%) of intermediate thinning (5-15 years)	0	98.8	9.2
Extent (%) of old thinning (>15-30 years)	0	25.0	0.5

*sawlog removal.

Results

Annual rainfall

Annual rainfall in the calendar year preceding surveys was variable but generally well below the long-term average for Eden (846 mm; BOM weather station ID: 069015 - Eden (Marine Rescue Eden)), especially in the last four years of the monitoring program (Fig. 3).

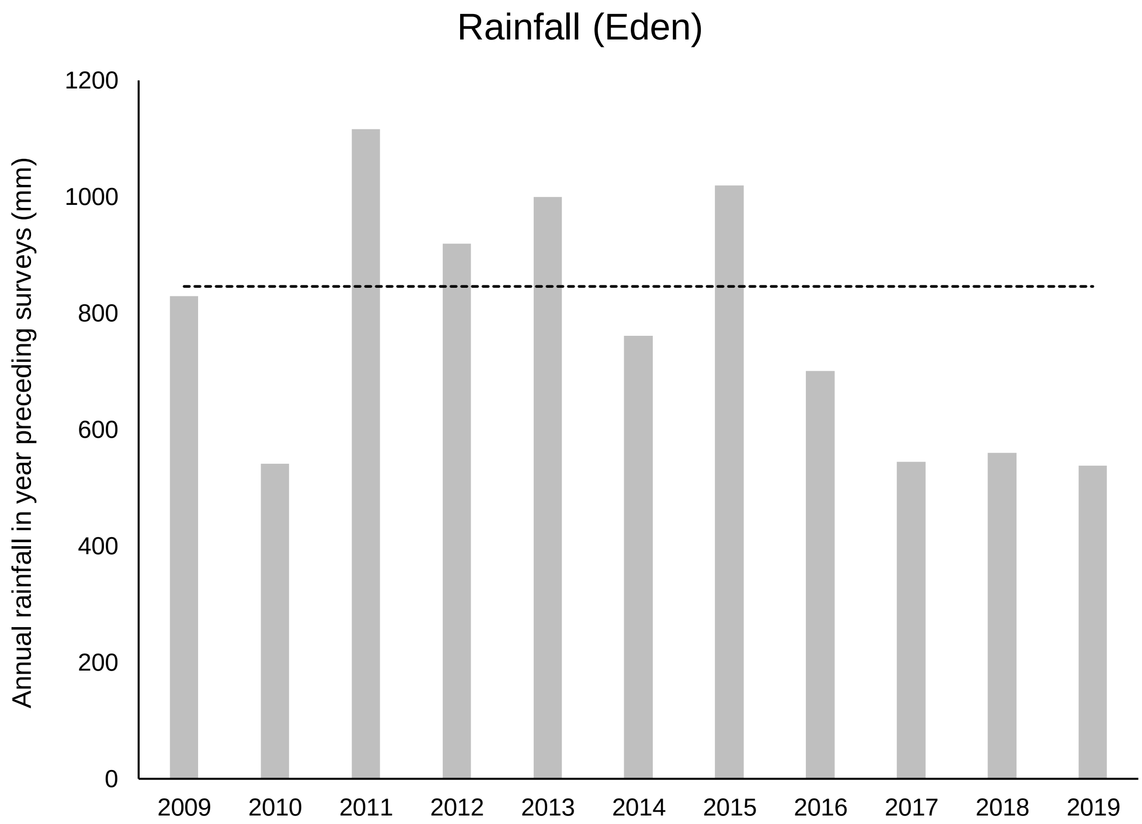


Fig. 3. Column graph illustrating annual calendar year rainfall in the year preceding surveys. Dashed line indicates long-term average (846 mm per annum).

Annual disturbance (fire and harvesting)

The extent of fire, harvesting (sawlog removal) and thinning of different age classes across monitoring sites was variable among years (Table 3).

Table 3. Total extent of fire, harvesting (sawlog removal) and thinning within 200 m buffer of all sites between 2009 and 2019.

Year	Extent of fire within 200 m buffer (ha)				Extent of harvesting within 200 m buffer (ha)				Extent of thinning within 200 m buffer (ha)		
	<5 yrs	5 to 15 yrs	15 to 30 yrs	> 30 yrs	<5 yrs	5 to 15 yrs	15 to 30 yrs	> 30 yrs	<5 yrs	5 to 15 yrs	15 to 30 yrs
2009	58	225	96	65	1	46	93	169	46	5	0
2010	75	179	107	82	1	39	87	181	44	18	0
2011	75	169	97	103	0	37	69	202	51	18	0
2012	62	136	143	103	0	28	76	205	56	26	0
2013	73	137	117	115	1	15	64	230	46	37	0
2014	60	148	120	115	5	15	63	231	33	49	2
2015	41	94	180	128	9	15	63	231	22	60	2
2016	47	101	180	128	9	9	69	231	19	64	5
2017	48	101	180	127	13	7	65	238	6	77	5
2018	45	64	221	127	17	4	68	234	5	78	5
2019	36	86	210	127	21	7	63	231	4	79	5

Camera trapping summary results

Among all years of monitoring, 70,699 images contained fauna that were assigned to a species, genus, broader group (reptile, small mammal, macropod, etc.) or were unable to be identified. Of these, 2103 images were assigned as definite SBB, representing 334 detections across all sites and years of monitoring. In all, 674 images of key predators (foxes, cats and dogs) were recorded. The activity (total no. of images) of key predators was variable among years. Overall, fox and wild dog activity was low, whereas cat activity was relatively higher (Table 4).

Table 4. Total number of images of predators detected on cameras between 2009 and 2019.

Year	Foxes		Cats		Wild Dogs	
	No. of images	No. of sites	No. of images	No. of sites	No. of images	No. of sites
2009	0	0	0	0	10	4
2010	13	4	54	14	19	7
2011	1	1	52	12	30	9
2012	7	2	43	14	22	8
2013	1	1	54	12	7	3
2014	2	1	91	11	7	4
2015	0	0	45	11	7	3
2016	0	0	49	14	5	3
2017	5	1	62	16	10	4
2018	1	1	39	14	4	3
2019	4	3	13	9	5	4

Naïve occupancy

Naïve occupancy, for SBB, which does not account for imperfect detection associated with surveys, ranged between 0.08 and 0.55 and fluctuated between years (Table 1).

Detection

A single candidate model that allowed detection probability to vary with season was supported (Table 5). Daily detection probability was marginally (4%) higher in autumn (0.12) compared to spring (0.08), but still relatively low (Fig. 4). This is similar to a previous estimate found for the same species in the Grampians (Rudolph et al. 2010). Use of one or two cameras per site was not supported as an influence on detectability based on AIC.

Table 5. List of models for Southern Brown Bandicoot detection probability. Supported models are shaded in grey.

Model	dAIC	weight	npar	n2ll
psi(.),gam(.),eps(.),p(season)	0	0.9951	5	2507.37
psi(.),gam(.),eps(.),p(.)	11.3	0.0035	4	2520.68
psi(.),gam(.),eps(.),p(effort)	13.13	0.0014	5	2520.5

Season = Autumn or Spring.
Effort = # camera trap nights

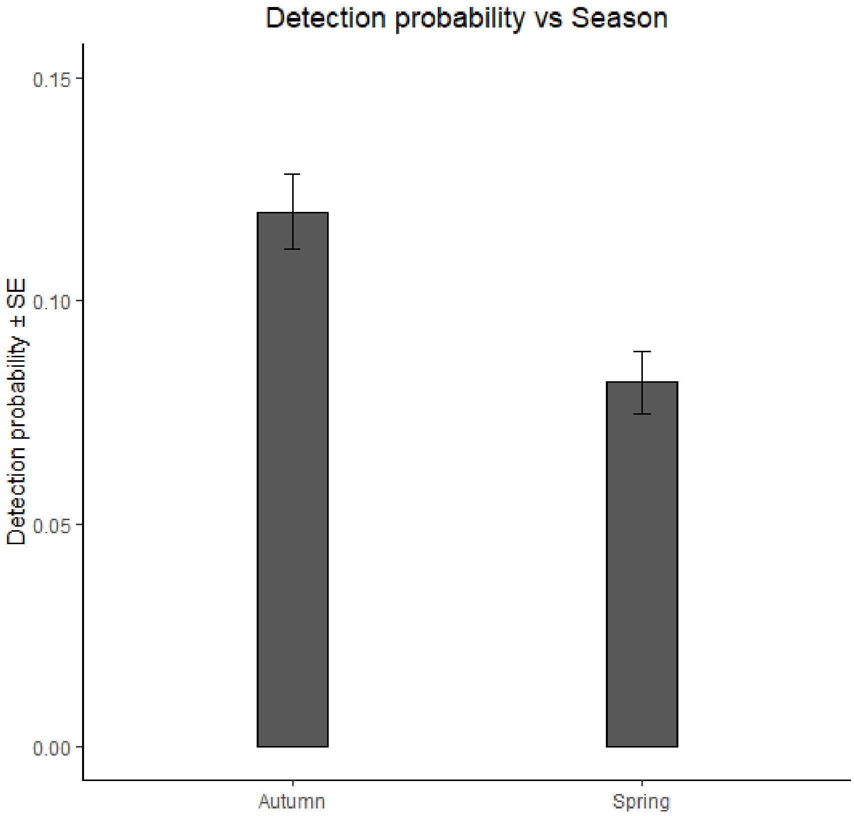


Fig. 4. Plot illustrating the influence of season on daily detection probability for Southern Brown Bandicoot.

Initial (2009) occupancy

In all, 26 candidate models assessed as potential explanatory variables for initial occupancy for SBBs (Table 6). Two models had support, with the top model having more than double the weight of the other supported model, indicating less of an influence on initial occupancy for covariates in the second model. The top model allowed initial occupancy to vary with topographic position (TPI) whereas the other supported model allowed initial occupancy to vary with understorey cover (LiDAR density at 6-8 m).

Table 6. List of models for Southern Brown Bandicoot initial occupancy. Supported models are shaded in grey.

Model	dAIC	weight	npar	n2ll
psi(tpi),gam(.),eps(.),p(season)	0	0.2956	6	2500.91
psi(lidar_6-8m),gam(.),eps(.),p(season)	1.7	0.1262	6	2502.62
psi(lidar_8-10m),gam(.),eps(.),p(season)	2.52	0.0838	6	2503.43
psi(fire),gam(.),eps(.),p(season)	2.66	0.0781	9	2497.57
psi(thinning),gam(.),eps(.),p(season)	3.17	0.0606	7	2502.08
psi(woollybutt_mixed coastal eucalypt),gam(.),eps(.),p(season)	3.74	0.0455	6	2504.66
psi(.),gam(.),eps(.),p(season)	4.46	0.0318	5	2507.37
psi(lidar_4-6m),gam(.),eps(.),p(season)	4.5	0.0311	6	2505.42
psi(lidar_10-12m),gam(.),eps(.),p(season)	4.98	0.0245	6	2505.89
psi(non-forest/she-oak/scrub/rainforest),gam(.),eps(.),p(season)	5.14	0.0226	6	2506.06
psi(lidar_12-14m),gam(.),eps(.),p(season)	5.78	0.0164	6	2506.69
psi(elevation),gam(.),eps(.),p(season)	5.95	0.0151	6	2506.87
psi(yertchuk communities),gam(.),eps(.),p(season)	6.09	0.0141	6	2507
psi(silvertop ash communities),gam(.),eps(.),p(season)	6.26	0.0129	6	2507.18
psi(stringybark/coastal),gam(.),eps(.),p(season)	6.34	0.0124	6	2507.25
psi(habitat exclusion),gam(.),eps(.),p(season)	6.38	0.0122	6	2507.29
psi(non-exclusion),gam(.),eps(.),p(season)	6.38	0.0122	6	2507.29
psi(lidar_2-4m),gam(.),eps(.),p(season)	6.39	0.0121	6	2507.3
psi(canopy height),gam(.),eps(.),p(season)	6.41	0.012	6	2507.32
psi(lidar_0-2m),gam(.),eps(.),p(season)	6.43	0.0119	6	2507.34
psi(lidar_14-15m),gam(.),eps(.),p(season)	6.43	0.0119	6	2507.34
psi(messmate/yellow stringybark communities),gam(.),eps(.),p(season)	6.44	0.0118	6	2507.35
psi(canopy cover),gam(.),eps(.),p(season)	6.46	0.0117	6	2507.37
psi(rainfall),gam(.),eps(.),p(season)	6.46	0.0117	6	2507.37
psi(harvesting),gam(.),eps(.),p(season)	7.23	0.008	9	2502.14
psi(ft),gam(.),eps(.),p(season)	10.26	0.0017	10	2503.17

tpi = topographic position index.

lidar_0-2m, lidar_2-4m; lidar_4-6m, lidar_6-8m, lidar_8-10m, lidar_10-12m, lidar_12-14m and lidar_14-15m = cover derived from LiDAR at different height classes/bins.
canopy cover = canopy cover derived from LiDAR.
canopy height = average height of canopy derived from LiDAR.
woollybutt mixed coastal eucalypt, silvertop ash communities, messmate/yellow stringybark communities, yertchuk communities, non-forest/she-oak/scrub/rainforest, stringybark/coastal = extent of each broad forest type.
ft = an additive model with the extent of each broad forest type.
thinning = extent of thinning of three age classes: (recent; <5 years), (intermediate; 5-15 years) and (old; >15-30 years) in an additive model.
harvesting = extent of harvesting of four age classes (recent; <5 years), (intermediate; 5-15 years), (old; >15-30 years) and (long undisturbed; >30 years) in an additive model.
fire = extent of fire of four age classes (recent; <5 years), (intermediate; 5-15 years), (old; >15-30 years) and (long undisturbed; >30 years) in an additive model.
habitat exclusion = extent of SBB habitat exclusion.
non-exclusion = extent of non-SBB habitat exclusion.
rainfall = total rainfall in the calendar year preceding sampling.
elevation = average elevation of camera locations at each site.

Initial occupancy was strongly influenced by topographic position with occupancy greatest on upper slopes and declining along a ridge-gully gradient (Fig. 5a). Initial occupancy was also negatively associated with understorey cover in the 6-8 m height bin (based on LiDAR) (Fig. 5b). Error bars were relatively wide for these relationships most likely because of the low number of sites in the monitoring program, suggesting a degree of caution in interpreting these patterns.

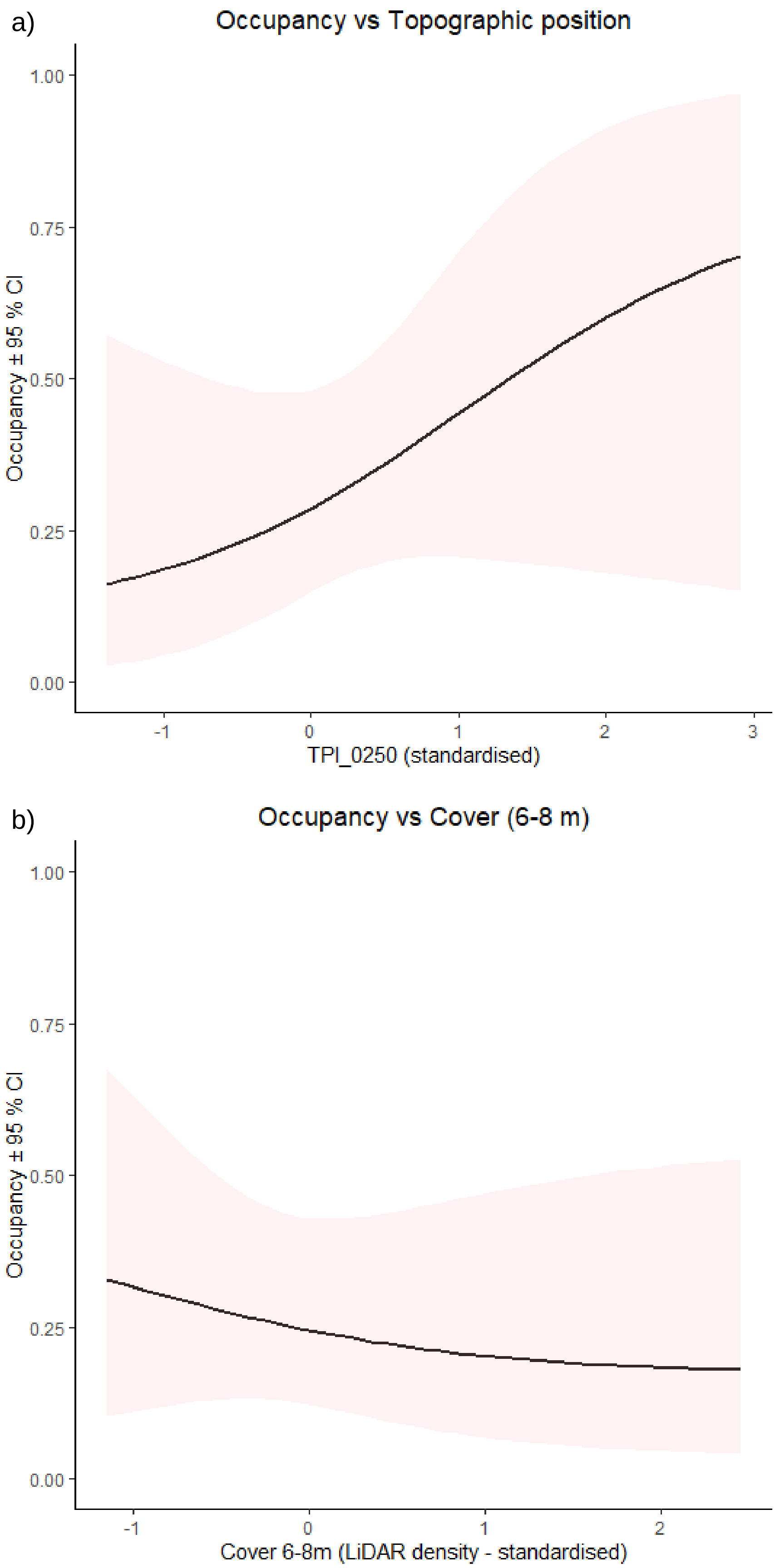


Fig. 5. Relationships between initial occupancy and: a) Topographic position index (TPI_0250) and b) LiDAR density at 6-8 m.

Colonisation and Extinction

In all, six candidate models assessed extinction probability for SBBs (Table 7). A single model was supported which allowed extinction probability to vary with the extent of fire of all age classes. While the extents of all fire age classes were included in this model as additive terms, the main influence on extinction probability was from the extent of intermediate (5-15 years) age fires which negatively influenced extinction probability. This relationship had a high degree of certainty, unlike the relationships for other fire age classes (Fig. 6a-d). Extinction was estimated to be < 5 % when these fires burnt ≥ 10 % of the surrounding buffer. Extent of recent fire (< 5 years) had an increased probability of extinction, but the relationship had a high degree of uncertainty.

Table 7. List of models for Southern Brown Bandicoot extinction probability. Supported models are shaded in grey.

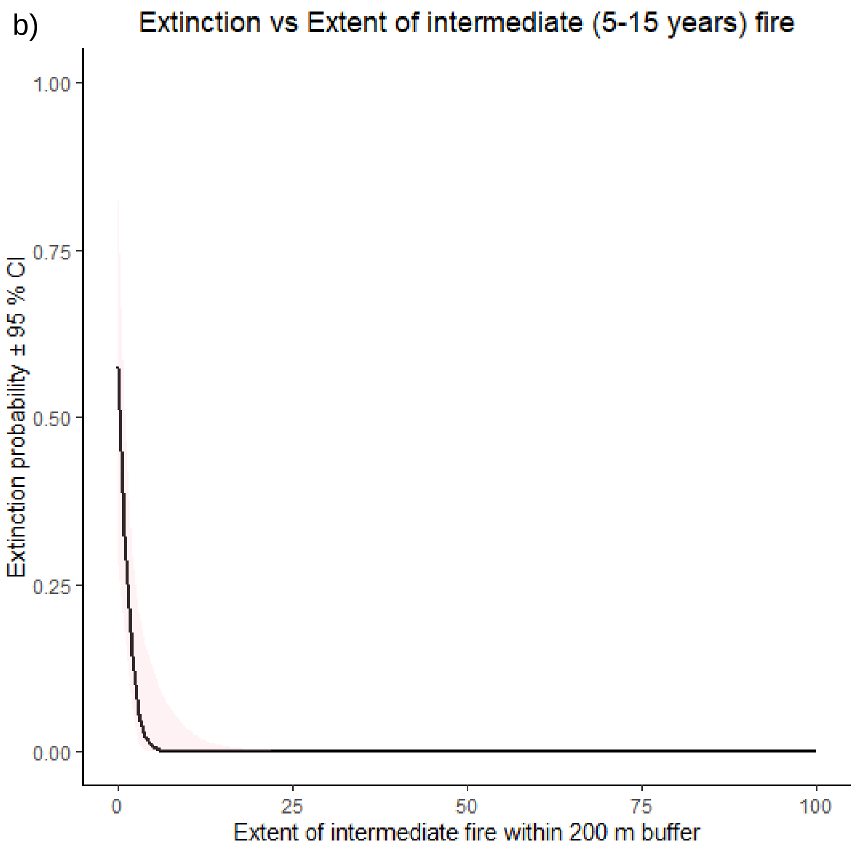
Model	dAIC	weight	npar	n2ll
psi(tpi),gam(.),eps(fire),p(season)	0	0.997	10	2475.67
psi(tpi),gam(.),eps(harvesting),p(season)	13.26	0.0013	10	2488.93
psi(tpi),gam(.),eps(rainfall),p(season)	13.88	0.001	7	2495.54
psi(tpi),gam(.),eps(cat activity),p(season)	14.99	0.0006	7	2496.66
psi(tpi),gam(.),eps(.),p(season)	17.25	0.0002	6	2500.91
psi(tpi),gam(.),eps(thinning),p(season)	21.43	0	9	2499.1

thinning = extent of thinning of three age classes: (recent; <5 years), (intermediate; 5-15 years) and (old; >15-30 years) in an additive model.
harvesting = extent of harvesting of four age classes (recent; <5 years), (intermediate; 5-15 years), (old; >15-30 years) and (long undisturbed; >30 years) in an additive model.
fire = extent of fire of four age classes (recent; <5 years), (intermediate; 5-15 years), (old; >15-30 years) and (long undisturbed; >30 years) in an additive model.
rainfall = total rainfall in the calendar year preceding sampling.
cat activity = total number of cat images recorded at each site.

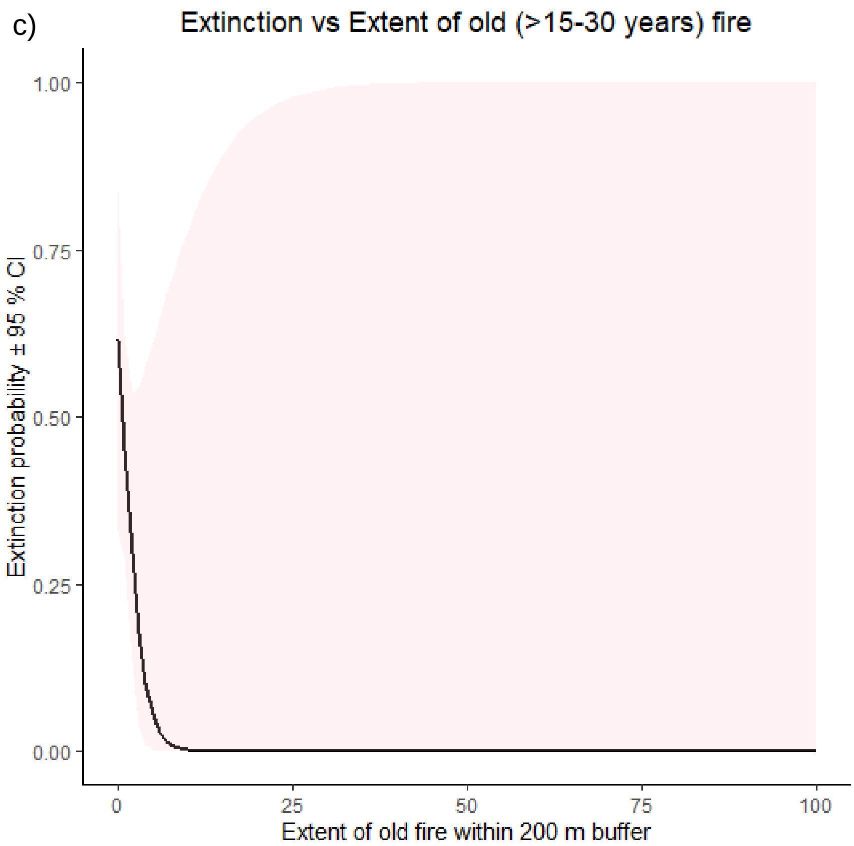
a)


Extinction vs Extent of recent (<5 years) fire
Extinction probability ± 95 % CI
1.00
0.75
0.50
0.25
0.00
0
25
50
75
100
Extent of recent fire within 200 m buffer (%)

b)


Extinction vs Extent of intermediate (5-15 years) fire
Extinction probability ± 95 % CI
1.00
0.75
0.50
0.25
0.00
0
25
50
75
100
Extent of intermediate fire within 200 m buffer

c)


Extinction vs Extent of old (>15-30 years) fire
Extinction probability ± 95 % CI
1.00
0.75
0.50
0.25
0.00
0
25
50
75
100
Extent of old fire within 200 m buffer

d)

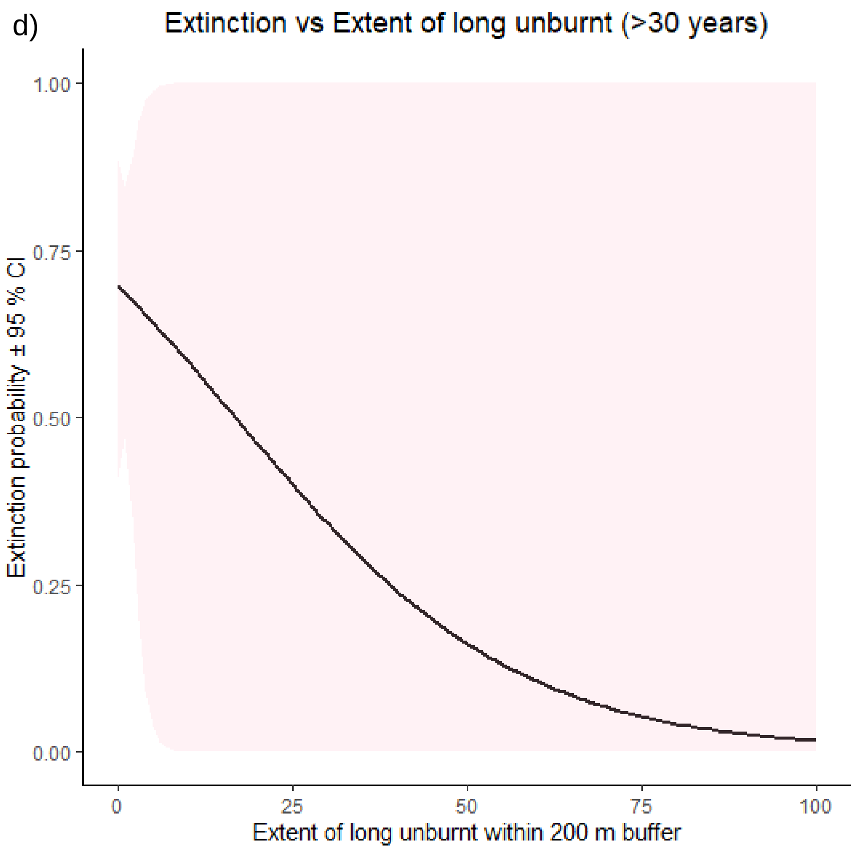

Extinction vs Extent of long unburnt (>30 years)
Extinction probability ± 95 % CI
1.00
0.75
0.50
0.25
0.00
0
25
50
75
100
Extent of long unburnt within 200 m buffer

Fig. 6. Relationships between extinction probability and extent of fire of different age classes: a) recent (<5 years), b) intermediate (5-15 years), c) old (>15-30 years) and d) long unburnt (>30 years).

In all, six candidate models assessed colonisation probability for SBBs (Table 8). A single model was supported which allowed colonisation probability to vary with the amount of rainfall in the calendar year preceding surveys. Colonisation was >0.2 when rainfall was equivalent to or above the long-term average for the study area (846 mm) (Fig. 7).

Table 8. List of models for colonisation probability. Supported models are shaded in grey.

Model	dAIC	weight	npar	n2ll
psi(tpi),gam(rainfall),eps(fire),p(season)	0	0.8948	11	2468.36
psi(tpi),gam(.),eps(fire),p(season)	5.3	0.0631	10	2475.67
psi(tpi),gam(cat activity),eps(fire),p(season)	7.24	0.0239	11	2475.6
psi(tpi),gam(harvesting),eps(fire),p(season)	8.91	0.0104	14	2471.27
psi(tpi),gam(thinning),eps(fire),p(season)	10.39	0.005	13	2474.75
psi(tpi),gam(fire),eps(fire),p(season)	11.56	0.0028	14	2473.92

thinning = extent of thinning of three age classes: (recent; <5 years), (intermediate; 5-15 years) and (old; >15-30 years) in an additive model.
harvesting = extent of harvesting of four age classes (recent; <5 years), (intermediate; 5-15 years), (old; >15-30 years) and (long undisturbed; >30 years) in an additive model.
fire = extent of fire of four age classes (recent; <5 years), (intermediate; 5-15 years), (old; >15-30 years) and (long undisturbed; >30 years) in an additive model.
rainfall = total rainfall in the calendar year preceding sampling.
cat activity = total number of cat images recorded at each site.

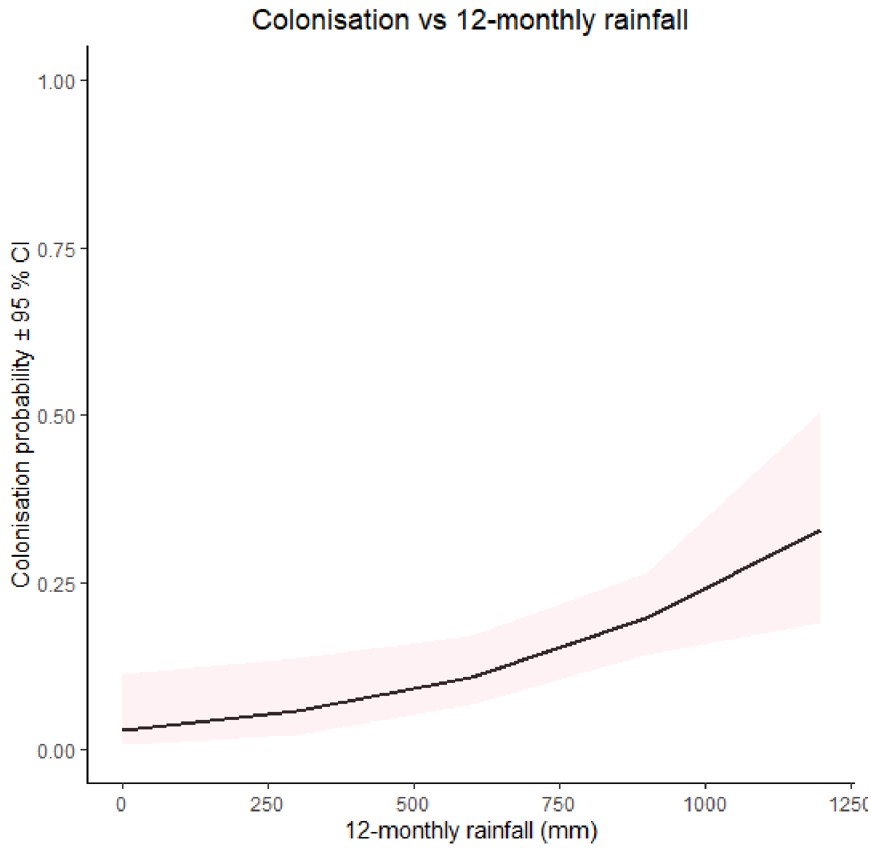


Fig. 7. Relationships between colonisation probability and the amount of rainfall in the calendar year preceding surveys.

Trend

Multi-season modelling of Southern Brown Bandicoot occupancy, calculated assuming median topographic position of the monitoring sites (lower slopes/gully), was relatively low over the period (2009-2019) of monitoring and has decreased by ~46 % from 0.24 in 2009/10 to 0.13 in 2019 (Fig. 8). Occupancy fluctuated between years but was relatively stable between 2009/10 and 2013 before showing a decline in 2014 and 2015 and then stabilising to a low level in subsequent years. A moderate level of precision is evident for the trend and additional sites would be needed to increase precision.

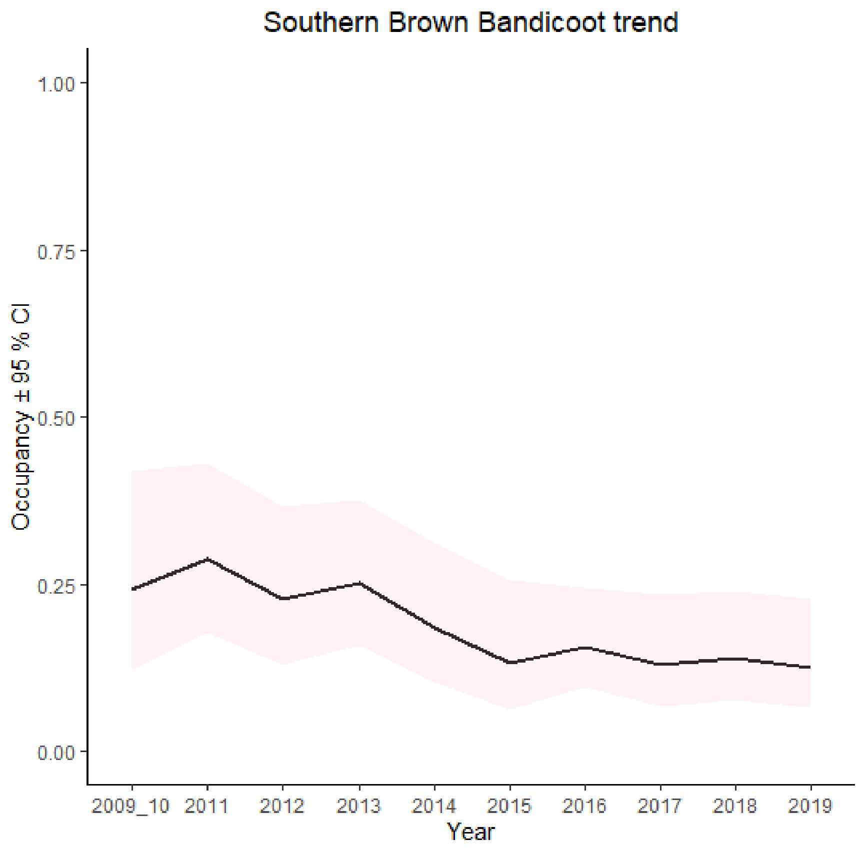


Fig. 8. The trend for Southern Brown Bandicoot multi-season occupancy between 2009 and 2019. Dashed lines are 95 % confidence intervals. Trends are calculated assuming median topographic position (equivalent to lower slopes/gully) when calculating initial occupancy.

Limitations

The major limitation for this analysis was the relatively low number of sites (n=40 sites) required for occupancy analyses that resulted from pooling adjacent cameras to the site level (n=80 cameras). This resulted in often low precision for relationships with covariates. Nonetheless, the long-time series achieved in a moderate level of precision for the trend in occupancy over time.

Several important potential drivers (e.g., harvesting and fire) of trends in occupancy of SBBs across monitoring sites were captured for analysis, there were others that were not routinely available for each year of the monitoring program. Detection of SBBs has been shown to be negatively associated with shrub cover elsewhere (Claridge et al. 2019). LiDAR data captured early on in the monitoring program provided some measure of cover of different vertical profiles that could be related to initial occupancy. However, it was not possible to assess whether such cover had changed over time and also whether this influenced colonisation and/or extinction. Having some measure of habitat complexity for each year of monitoring would be instructive.

Another limitation of the study was associated with the low detection rate in the first year of monitoring (2009). Naïve occupancy (0.08) in this year was the lowest for the monitoring period evaluated to date. This may be partly due to sampling only occurring in spring for this year, with this season having a lower detection probability than autumn which was sampled in addition to spring in all other years. The dynamic occupancy modelling framework used in this study establishes initial occupancy (in year 1 of monitoring) and then derives estimates of occupancy for subsequent years based on relationships established for colonisation and extinction. Since so few detections were recorded in year 1 of monitoring, estimates for initial occupancy were likely to be highly uncertain. To account for this, we pooled data from 2009 and 2010 to establish more reliable relationships for initial occupancy and assumed conditions recorded in 2010 were present for records from 2009. Any influence of this assumption is moderated by use of disturbance age classes (e.g., a record is associated with disturbance up to 4 years old in the recent age class).

The reliability of spatial layers available to calculate the extent of disturbance (fire and harvesting) in the local landscape of each sampling site should also be considered when interpreting results. For example, hazard reduction burn data was only available from 1992 onwards, which may mean that the mapped extent of older fire age classes may be an underestimate. Furthermore, early mapping of fire may have included patches that remained unburnt.

Another complication for the analysis is the potential for harvesting effects to be confounded with burning effects that resulted from a post-harvest burn, though this was not consistently applied after every harvesting operation. Presumably, future harvesting will also record whether a post-harvest burn was applied.

Interpretation of results

Detection probability for SBB varied with season of survey, with greater detection probability recorded for autumn (0.12 per day with two camera units) compared to spring (0.08 per day with two camera units). The greater detection in autumn may coincide with the peak in recruitment of juveniles into the population (Department of Sustainability, Environment, Water, Population and Communities 2011). Nevertheless, detection probability rates recorded for the SBB SMP monitoring program were similar to those recorded elsewhere (<0.1 at Nadgee, <0.15 at Ben Boyd; Claridge et al. 2019, and ~0.08 in the Grampians; Stevens et al. 2010).

Initial occupancy (2009/2010) was positively associated with topographic position index (TPI), indicating greater SBB occupancy on upper slopes and ridges relative to gullies. This preference for higher topographic locations has been reported previously for SBBs in a nearby dry eucalypt forest site in south-eastern NSW (Claridge et al. 1991). There was also a negative relationship between initial occupancy and vegetation (understorey) cover between 6-8 m in height, which aligns with recently published research in conservation reserves immediately adjacent to our study area (Claridge et al. 2019). That same study found that increasing density of very low ground cover instead favoured the chances of detecting the species. It is possible that sites with an open understorey (shrub) layer (6-8 m high) could be inversely related to ground cover (predator refuge), which might only be captured by high resolution Lidar.

Colonisation and extinction probability were associated with 12-monthly rainfall in the calendar year preceding surveys and the extent of fire of different ages, respectively. Other types of disturbance and the activity of a predator did not influence colonisation or extinction. Greater relative extents of intermediate (5-15 year) and older (>15-30 years) age class fires were associated with reduced extinction probability, though with a greater degree of uncertainty for the latter, potentially because of post-fire dense ground cover and a relatively low number of sites in this age class. Dynamics of ground cover after disturbance were not able to be modelled in this study, noting LiDAR captures a static picture of cover in the year it is captured and temporal LiDAR transects were not available. Recent fire had a weaker effect of increasing extinction, probably because of reduced cover against predators (cats). These results parallel those reported in the Grampians where SBB peaked in occupancy 15-20 years post fire (and again > 50 years since fire) (Hale et al. 2016).

The study by Hale et al. (2016) also recorded a strong negative effect of drought (previous 18 month rainfall), which is supported by the positive relationship between colonisation and rainfall in the calendar year preceding surveys in the current study. Rainfall in the last four years of the monitoring time series was well below the long-term average for the study area and this may in part reflect the lower occupancy levels relative to the start of the monitoring program, when rainfall was equivalent to or higher than the long-term average for four of the first five years of the program. Elsewhere, rainfall did not have significant effects on the population dynamics of ground mammals though specific results for bandicoot species were pooled together due to limitations in the sampling method (tracks in sand plots; Arthur et al. 2012). In the Otway ranges of Victoria, terrestrial mammal occurrences (though noting SBB was not included in the study) were more strongly affected by habitat complexity than time since fire, coarse woody debris cover, or invasive predator (fox or cat) occurrence (Hradsky et al. 2017).

Given we were unable to provide a reliable dynamic measure of habitat complexity, time since fire and harvesting most likely served as the nearest best surrogates, though the relative scales of both disturbances vary substantially in the study area. These results contrast with those of Dixon et al. (2019), who found that significantly more species were detected at long-unburnt sites (>96 years since fire) than sites with more recent fire (0.5–12 years since the last fire), though again SBB were not part of that study and the sub-alpine woodland is very different to the coastal sclerophyll forest. The varied response of different fauna emphasises the need for fire mosaics, and especially recognition of long unburnt patches, though this may not be beneficial for SBB. It is important to acknowledge that the SBB monitoring study was limited to fires and harvesting experienced at the monitoring sites rather than a gradient specifically designed to contrast some of these disturbances, which may have produced clearer results.

Widespread fox control in Victoria has also been found to increase occupancy rates of SBB, but this also interacted with rainfall (Robley et al. 2014) and potentially predation by feral cats (Arthur et al. 2012). Elsewhere in southeast Australian forests, the activity levels of bandicoots were not uniformly greater in areas subjected to fox baiting, as rainfall and habitat complexity potentially regulate activity (Claridge et al., 2010; Arthur et al. 2012). In the current study, feral cats were the most common and widespread predator with some fluctuation in occurrence among years. Few foxes were recorded (mostly at sites near human settlement) and wild dogs were intermediate. Feral cats likely have a role to play in preventing SBB occupancy from increasing above the low levels most recently recorded (~0.13 %) for the monitoring program, though cat activity was not associated with colonisation or extinction. Estimated occupancy in state forests was similar to that in nearby National Parks, with Ben Boyd (baited for foxes) supporting higher occupancy (even during a drier period) than Nadgee (unbaited) (Claridge et al. 2019).

The overall trend for SBB in the study area was that of a ~46 % decline in 10 years, though the decline has not been steady in nature, with occupancy fluctuating within the time series. For example, despite year-to-year fluctuations occupancy remained at ~0.24 between 2009/10 and 2013. A decline was evident in 2014 and 2015 before occupancy stabilised for the last four years of the monitoring program, albeit again with year-to-year fluctuations. The strong decline observed in 2014 and 2015 was associated with below average rainfall in the calendar year preceding 2014 surveys and a 36 % reduction in the extent of the intermediate fire (5-15 years) age class in 2015. Below-average rainfall in years following the decline likely prevented SBB occupancy from increasing above the levels reached during the decline. Consideration should be given to alternative management or further research given the 46 % decline over a 10-year period (i.e. decline > 30 % within 10 years), although widespread fires in 2019 limit some options.

Together the results of the SBB SMP monitoring program and previous research emphasise the importance of habitat complexity as a refuge from predation and the potential for these to interact with disturbance, particularly those that may affect larger areas within SBB habitat. The results also suggest that drought has a role to play in the population dynamics of SBB.

Recommendations

Management

- Habitat exclusion zones (16 out of 40 sites had no exclusion) and unlogged forest appeared to have little benefit for this species at the sites monitored given neither influenced occupancy or dynamic parameters (i.e., colonisation and extinction). However, we acknowledge the limitation of relatively low number of sites and suggest future monitoring expands the number of sites, specifically without exclusions to provide a more rigorous test of their effectiveness.
- Disperse harvesting treatments in space and time to ensure it continues to have a minor influence on SBB occupancy or dynamic parameters that influence occupancy.
- Give priority to maintaining an open understorey (shrub) layer, which is potentially related to denser ground cover in SBB habitat. Effects of dense (e.g. *Allocasuarina)* regrowth post-harvesting should be a management consideration (see below).
- Review/reconsider how habitat is defined for the SBB. Greater weight should be given to upper slopes where understorey (shrub) cover is open. Particular forest types (e.g., Yertchuk) do not appear to have a strong association with SBB occupancy, rather preferred habitat occurs under a range of different forest types.
- Aim for mosaic burning patterns that maximise the extent of 5-15 year age class in SBB habitat, especially previously harvested sites > 10 years in age where a high density of understorey (shrubs and saplings, e.g. *Allocasuarina* and eucalypt regrowth) may dominate.
- Re-establish fox baiting program and assess methods for controlling feral cats. It is possible that fox baiting helped to ameliorate the effects of drought prior to 2018, but it could also have allowed increased feral cat activity and cat predation. Any new

baiting program should be accompanied with monitoring to assess effectiveness and consider keeping some sites unbaited for comparison (e.g. Claridge et al. 2019).

Monitoring

- Continue to monitor SBB given recent widespread megafires, above-average rainfall following 2019, and SBB's rare status and low occupancy in study areas, but include a measure of habitat complexity each year to specifically record ground cover and taller understorey cover (e.g. Claridge et al. 2019 or Hradsky et al. 2017).
- Continue with two cameras per site to avoid drop in detection probability and maintain peanut butter and oats bait to be consistent with previous monitoring, noting that higher detection probability for the genus *Isoodon* is associated with truffle oil (Paull et al. 2011).
- Review sampling design.

  - The existing design may be amended to increase duration of deployments beyond 14 days (30 days - Claridge et al. 2019) in autumn when detection probability is greater. i.e., focus sampling effort in autumn instead of sampling in spring. Declining detection rates with time since deployment (14-day period) has been reported for the genus *Isoodon* (Paull et al. 2011), so an assessment should be made early on to establish whether the trade-off of ceasing spring sampling is offset by longer duration sampling in autumn.

  - Add additional sites to target higher suitability habitat (upper slope areas with less understorey cover), but without exclusion areas.
- Regularly tag photos and maintain careful record keeping of dates that cameras were deployed.
- Undertake analysis of data more frequently (e.g., every three years) to assess whether management is affecting (positively or negatively) trends in SBB occupancy.
- Analyse other species from dataset, giving priority to long-nosed potoroos, which were more commonly recorded than SBB.

Acknowledgements

Christopher O'Loughlin (NSW DPI) tagged all images in the 2009-2019 dataset and SBB were confirmed by Rohan Bilney. Rohan Bilney and Tony Brown (FCNSW) supplied spatial covariate data used in the analysis. We thank Rohan and Chris Slade (FCNSW) for providing comments on an early draft and Andrew Claridge (NSW DPI) for his formal review.

References

Arthur, A.D., Catling, P.C., Reid, A. (2012). Relative influence of habitat structure, species interactions and rainfall on the post-fire population dynamics of ground-dwelling vertebrates. *Austral Ecology*, 37, 958–970.

Claridge, A.W., Cunningham, R.B., Catling, P.C., Reid, A.M. (2010). Trends in activity levels of forest-dwelling vertebrate fauna against a background of intensive baiting for foxes. *Forest Ecology and Management*, 260, 822–832.

Claridge, A. W., Paull, D. J., Welbourne, D.J. (2019). Elucidating patterns in the occurrence of threatened ground-dwelling marsupials using camera-traps. *Animals*, 9, 913.

Claridge A.W., McNee, A., Tanton, M.T., Davey, S.M. (1991). The ecology of bandicoots in undisturbed forest adjacent to logging coupes: a case study from the Eden Woodchip Agreement Area. In: Conservation of Australia's Forest Fauna (ed. D. Lunney) pp. 331–45. Royal Zoological Society of New South Wales, Mosman.

Department of Sustainability, Environment, Water, Population and Communities. (2011). Environment Protection and Biodiversity Conservation Act 1999 draft referral guidelines for the endangered southern brown bandicoot (eastern), *Isoodon obesulus*. Accessed via: https://www.environment.gov.au/system/files/resources/e03156ce-3dbe-496e-bc18-fad2b38a3978/files/southern-brown-bandicoot.pdf

Dixon, K.M., Cary, G.J., Renton, M., Worboys, G.L. and Gibbons, P. (2019), More long-unburnt forest will benefit mammals in Australian sub-alpine forests and woodlands. *Austral Ecology,* 44: 1150-1162. https://doi.org/10.1111/aec.12786

Hale, S., Nimmo, D.G., Cooke, R., Holland, G., James, S., Stevens, M., De Bondi, N., Woods, R., Castle, M., Campbell, K., Senior, K., Cassidy, S., Duffy, R., Holmes, B. and White, J.G. (2016). Fire and climatic extremes shape mammal distributions in a fire-prone landscape. *Diversity and Distributions*, 22, 1127-1138. https://doi.org/10.1111/ddi.12471

Hradsky, B.A., Penman, T.D., Ababei, D., Hanea, A., Ritchie, E.G., York, A., and Di Stefano, J. (2017). Bayesian networks elucidate interactions between fire and other drivers of terrestrial fauna distributions. *Ecosphere*, 8:e01926. 10.1002/ecs2.1926

Paull, D.J., Claridge, A.W., and Barry, S.C. (2011). There's no accounting for taste: bait attractants and infrared digital cameras for detecting small to medium ground-dwelling mammals. *Wildlife Research*, 38, 188-195.

Robley, A., Gormley, A.M., Forsyth, D.M., Triggs, B. (2014) Long-term and large-scale control of the introduced red fox increases native mammal occupancy in Australian forests. *Biological Conservation*, 180, 262-269.

Stevens, M., Rudolph, G., Christian, F., and Frey, S. (2010). Pilot survey for Long-nosed Potoroo and Southern Brown Bandicoot using remote camera in the Grampians National Park, February to April 2009. Field Report 3. Unpublished.