Quantifying mesopredator release: lethal control of an invasive apex predator changes feral cat density and detectability

Supporting Information

MW Rees, JH Pascoe, M Le Pla, A Robley, EK Birnbaum, BA Wintle & BA Hradsky

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1 Survey methods

1.1 Otway Ranges timeline

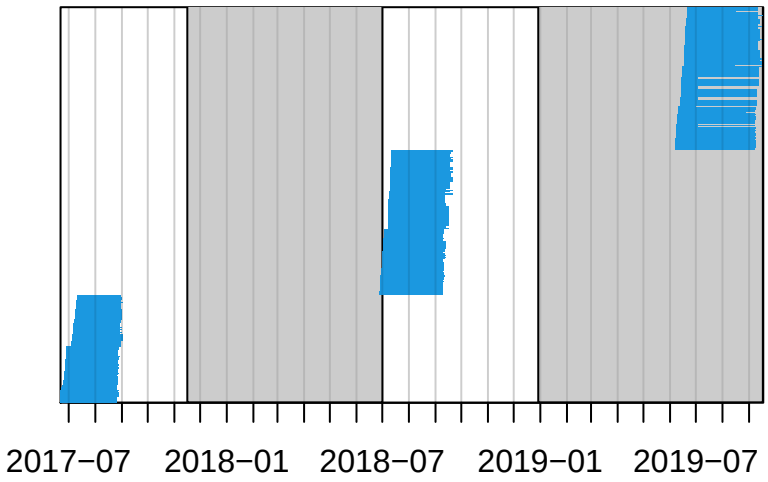

Figure 1: Camera-trap operation times in the Otway regions, Australia. Each blue horizontal line represents one camera-trap deployment. Grey shading indicates periods of fox control in the impact landscape.

1.2 Camera-trap deployment

In the Glenelg region, we deployed camera-traps once at a unique sites once. In the Otway region, we redeployed camera-traps in sites three times annually. All 2017 camera-sites were resurveyed each year, except for four logistically challenging sites in the southern grid. In 2018, we added 16 additional sites in the southern grid, as well as 36 additional sites in the northern grid. These additional sites were resurveyed in 2019.

At each site, we deployed a singular remote trail camera with infrared flash and temperature-in-motion detector. The vast majority of camera-traps were Reconyx Hyperfire HC600, but a small portion was made up of both PC900 and HF2X infrared models (Reconyx, Holmen, Wisconsin). We programmed camera's to the highest sensitivity and to take five consecutive photographs when triggered (no quiet period). We attached each camera to a tree, approximately 30 cm above the ground, and facing toward a lure 2 - 2.5 metres away. The lure comprised an oil-absorbing cloth doused in tuna oil and placed inside a PVC pipe container with a mesh top. We secured each lure to the top of a 1 metre wooden stake and attached a handful of small white feathers to the outside of the PVC pipe container. Feathers were not used in the Lower Glenelg National Park survey. We cleared vegetation in the camera's line-of-sight to reduce false triggers and avoid obscuring cat coat markings in images.

Figure 2: Example of a typical camera-trap set-up in the Otway region, Australia.

2 Individual cat identification

We first labelled every camera-trap image with a species metadata tag using DigiKam software. We also added metadata tags for each cat coat type: black, mackerel tabby, classic tabby, ginger and other (coats with multiple colour blends; Fig. 3). This allowed us to summarise species records and extract cat images using the 'camtrapR' R-package (Niedballa et al., 2016).

We considered all black cats to be of the 'unmarked' category in spatial mark-resight models - even the few with white splotches on their underside (as these couldn't always be seen as cats move with their head down).

In the remaining coat categories where possible, we identified individual cats based on their unique coat markings. The ability to identify individuals substantially increased as the image library for each cat increased. Therefore we made the easiest identifications first to build up these libraries, before making decisions on the less obvious detections. We examined and matched all coat markings seen between two particular defections. Markings on the front legs were the most useful for ID's as the patterns do not skew as much with different body positions. On the whole, unidentifiable detections were mainly due to only part of a cat appearing in the frame, or because photos were blurry (because of cat movement or a foggy camera lens).

We were left with a small number of instances (less than ten) where only left or right flanks could be seen. In this case, the side with the most repeat detections was labelled as an individual, whereas the side with the least number of detections was considered unidentifiable. Additionally, an extremely small portion of cats in the Otways had ginger coats. When ginger coats are photographed with an infrared flash, they become overexposed and no markings can be seen (see the image in bottom-right corner in Fig. S3). We only had one detection of a ginger cat without an infrared coat. Therefore, if there were multiple ginger cat detections in a single grid, we treated them in the same way as one-sided flank detections.

One observer identified the 2018 feral cats in the Glenelg region (MR) and the 2021 Lower Glenelg National Park cats (Luke Woodford). In the 2017 and 2018 Otway datasets (where there were substantially more cat detections and fewer distinct coat patterns) two independent observers identified individual cats and discrepancies between observers were reviewed together until consensus was reached (MR, MLP, BH). If no consensus was reached, the cat was considered unidentifiable. In the 2019 Otway dataset, many of the identified cats were sighted in the previous surveys – these larger individual libraries meant that cats could be identified more easily so only one observer was necessary (MR). We also made use of additional cat images taken within the Otway region grids (just before each of our surveys) by white flash camera-traps from another study (Zoï Banikos, unpublished data). This provided additional and higher quality images (due to the white flash) of individuals in the photo library for identifications.

We were therefore left with three groups of cats: unmarked (black cats), marked (cats which could be identified to the individual-level with complete certainty) and mark status unknown (cats which were not black, but couldn't be identified to the individual level with complete certainty).

We ignored the few detections of cats which were obviously young enough to be dependent on a parent, as these kittens do not have independent activity centres or movements and were not yet recruited into the adult population.

Figure 3: Feral cat coat categories from left-right, top-bottom: black, mackerel tabby, classic tabby, other, black, ginger and ginger with infrared flash.

3 Summary statistics

Table 1: Camera-trap surveys and feral cat spatial capture-recapture summary statistics.

Land-scape	Fox control?	Camera-traps	Trap nights	Identified cats	Identified detections	Unidentified detections	Unmarked detections
Annya	no	110	8000	9	23	3	20
Cobbob	yes	110	7752	13	35	9	37
Hotspur	no	99	6085	8	22	3	13
Mt Clay	yes	106	5451	10	33	5	0
LGNP north	no	49	2102	6	11	0	0
LGNP south	yes	64	2842	21	37	0	0
North 2017	no	67	3565	26	60	8	46
South 2017	no	73	7099	20	62	4	48
North 2018	lapsed	103	7838	30	90	12	62
South 2018	no	85	4543	24	75	17	59
North 2019	yes	99	6077	27	90	22	101
South 2019	no	86	7150	25	133	23	58

Note: There is a maximum of one detection per each 24-hour occasion.

4 Feral cat detection plots

4.1 Glenelg region

4.1.1 Replicate 1

a) Annya State Forest
78 occasions, 23 detections, 9 animals

b) Cobboboonee National Park
75 occasions, 35 detections, 13 animals

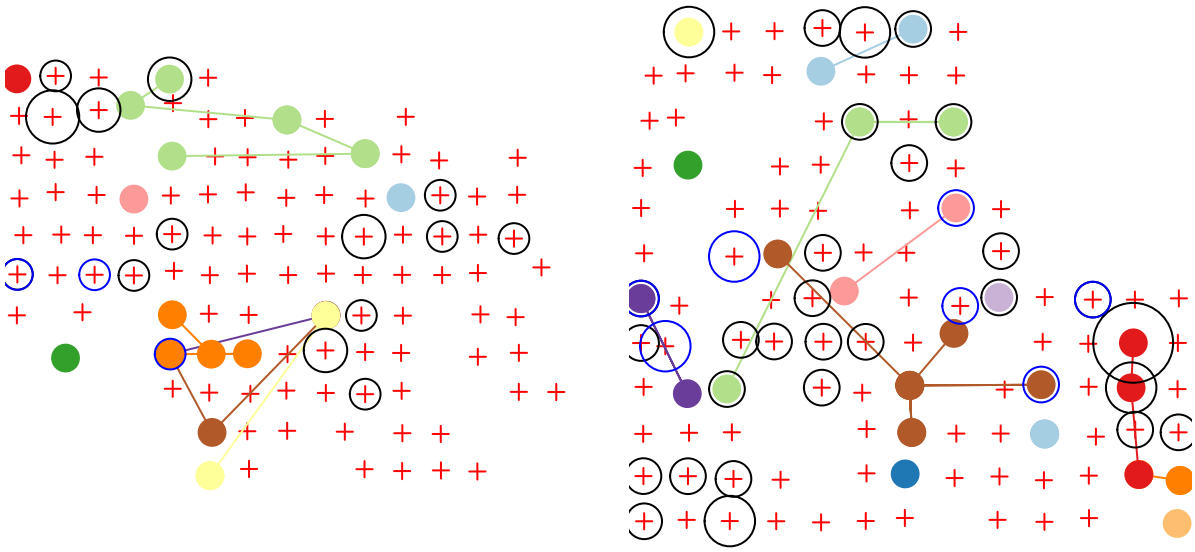

Figure 4: Feral cat detections in the first replicate grid pair in the Glenelg region, Australia. Camera-traps are indicated by red crosses. Solid fill coloured circles represent identified cats with lines indicating observed movements. Black open circles indicate black cat detections; blue circles indicate unidentifiable tabby cat detections, with circle radius scaling positively with the number of daily detections. Fox control does not occur in Annya (a) but does in Cobboboonee (b).

4.1.2 Replicate 2

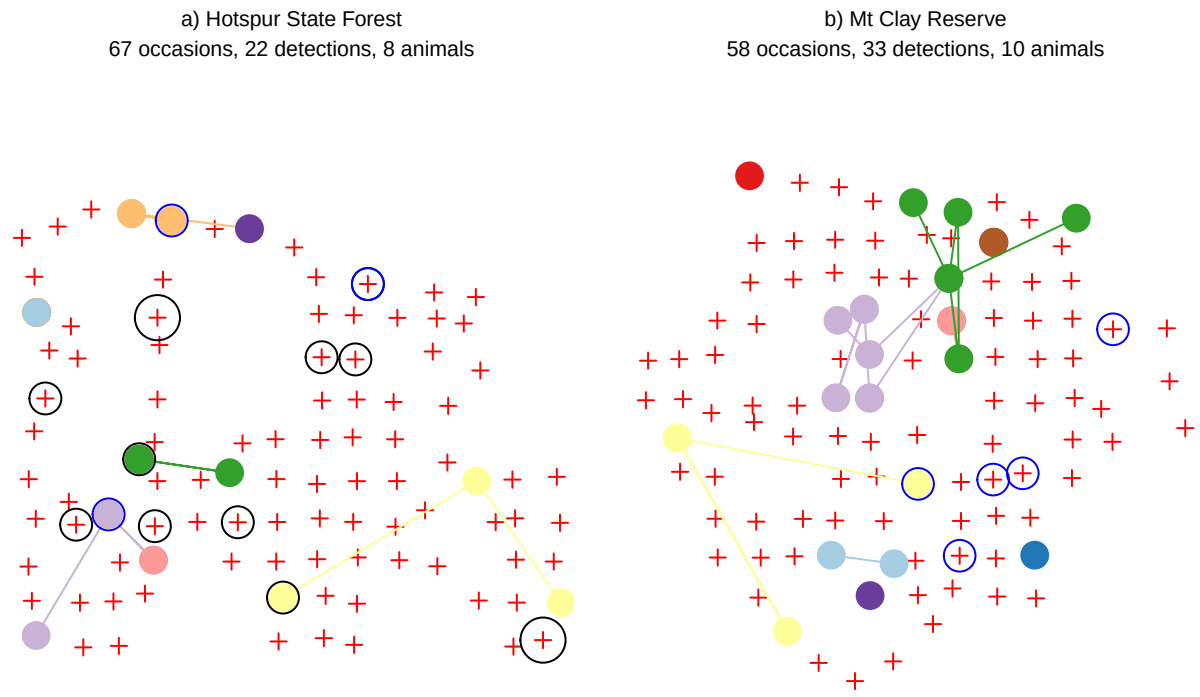

Figure 5: Feral cat detections in the second replicate grid pair in the Glenelg region, Australia. Camera-traps are indicated by red crosses. Solid fill coloured circles represent identified cats with lines indicating observed movements. Black open circles indicate black cat detections; blue circles indicate unidentifiable tabby cat detections, with circle radius scaling positively with the number of daily detections. Fox control does not occur in Hotspur (a) but does in Mt Clay (b).

4.1.3 Replicate 3

a) Lower Glenelg National Park − north
41 occasions, 11 detections, 6 animals

a) Lower Glenelg National Park − south
43 occasions, 37 detections, 21 animals

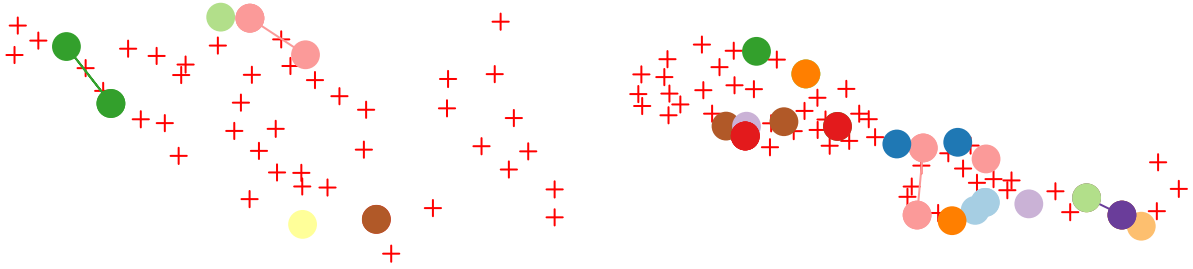

Figure 6: Feral cat detections in the third replicate grid pair in the Glenelg region, Australia. Camera-traps are indicated by red crosses. Solid fill coloured circles represent identified cats with lines indicating observed movements. Black open circles indicate black cat detections; blue circles indicate unidentifiable tabby cat detections, with circle radius scaling positively with the number of daily detections. Fox control does not occur in the north (a) but does in the south (b).

4.2 Otway region

4.2.1 2017

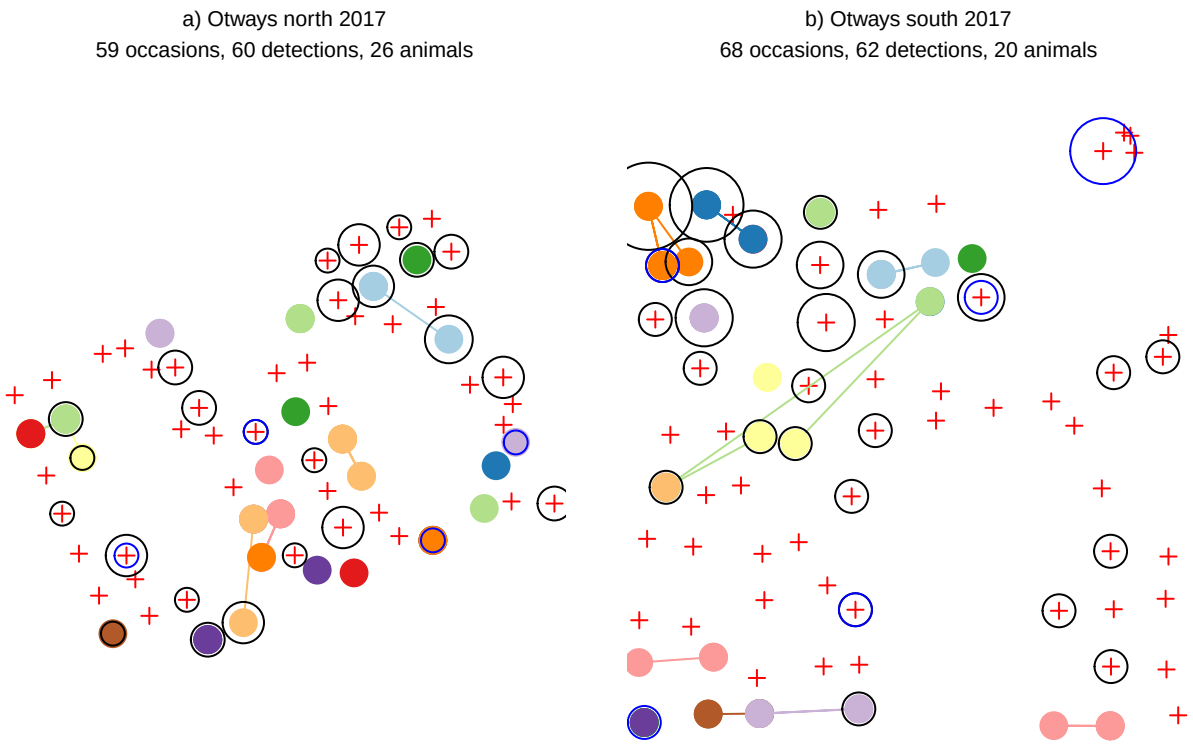

Figure 7: Feral cat detections in the Otway region, Australia, 2017. Solid fill coloured circles represent identified cats with lines indicating observed movements. Black open circles indicate black cat detections; blue circles indicate unidentifiable tabby cat detections, with circle radius scaling positively with the number of daily detections. Fox control did not occur in either of the landscapes during this time.

4.2.2 2018

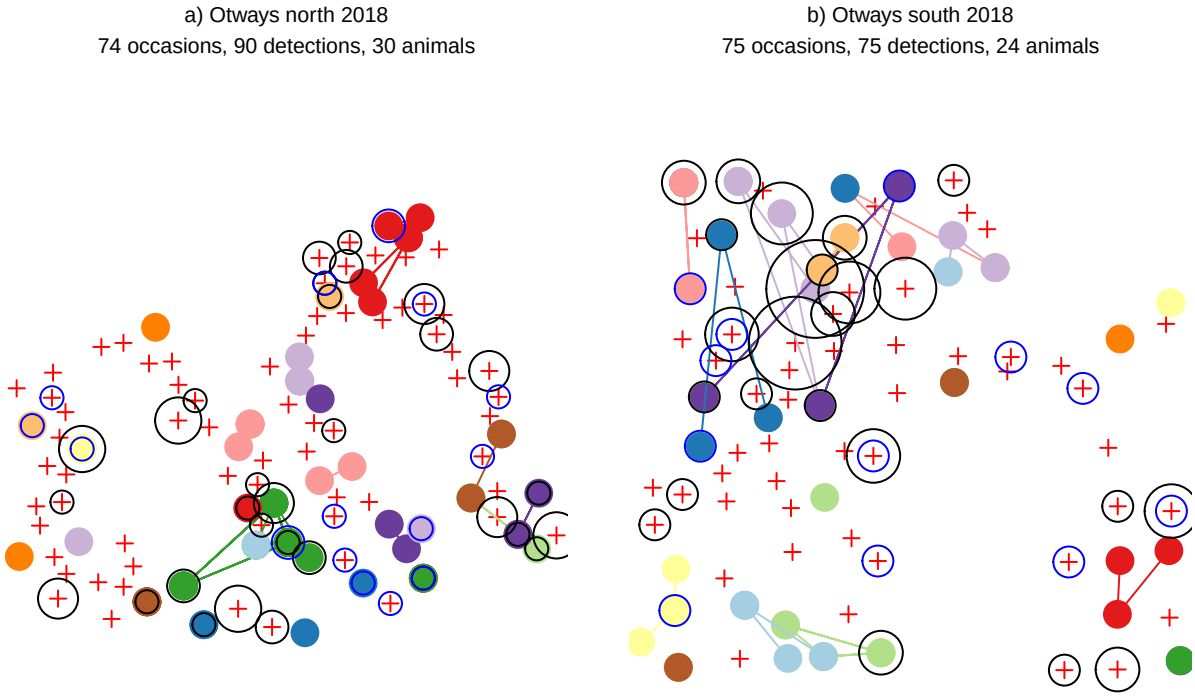

Figure 8: Feral cat detections in the Otway region, Australia, 2018. Solid fill coloured circles represent identified cats with lines indicating observed movements. Black open circles indicate black cat detections; blue circles indicate unidentifiable tabby cat detections, with circle radius scaling positively with the number of daily detections. Fox control had occurred, but lapsed just prior to the survey in the northern landscape (a), and did not occur in the southern landscape (b).

4.2.3 2019

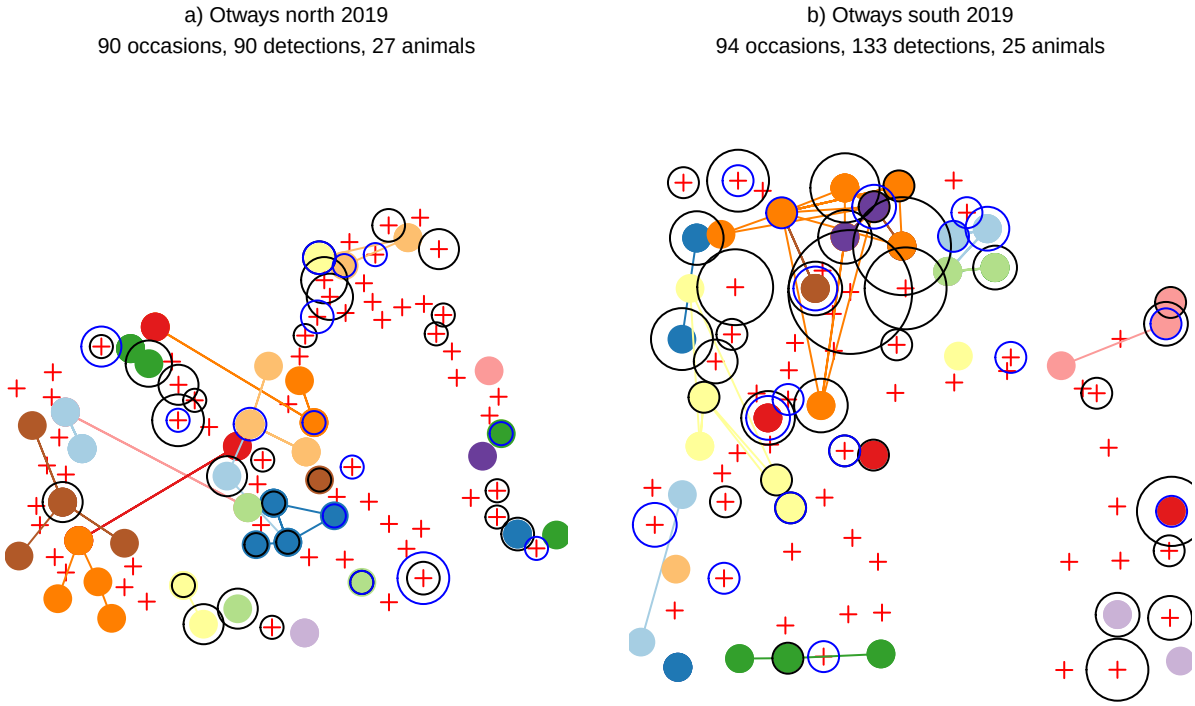

Figure 9: Feral cat detections in the Otway region, Australia, 2019. Solid fill coloured circles represent identified cats with lines indicating observed movements. Black open circles indicate black cat detections; blue circles indicate unidentifiable tabby cat detections, with circle radius scaling positively with the number of daily detections. Fox control occurred in the northern landscape (a) during this survey, but not the southern landscape (b).

5 Fox spatial occurrence

5.1 Glenelg region

```
##
## Family: binomial
## Link function: logit
##
## Formula:
## fox ~ s(x, y, bs = "ds", m = c(1, 0.5), k = 200) + offset(log(survey_duration))
##
## Parametric coefficients:
##             Estimate Std. Error z value            Pr(>|z|)
## (Intercept) -4.53965    0.09293  -48.85 <0.0000000000000002 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##          edf Ref.df Chi.sq     p-value
## s(x,y) 25.58    199  61.78 0.000000975 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.126   Deviance explained = 13.1%
## fREML = 845.52  Scale est. = 1         n = 538
```

```
##   station      x       y
## 1 LGNP065 510229 5793196
## 2 LGNP066 510147 5792476
## 3 LGNP067 510744 5792828
## 4 LGNP068 511450 5792683
## 5 LGNP069 511929 5792155
## 6 LGNP070 512994 5792630
```

```
## Reading layer 'LGNP_dissolved_32754' from data source '/Users/mrees2/Dropbox/personal/matt/github/C2
## Simple feature collection with 1 feature and 3 fields
## geometry type:  MULTIPOLYGON
## dimension:      XY
## bbox:           xmin: 496095.7 ymin: 5782517 xmax: 526544.5 ymax: 5797484
## CRS:            32754
```

```
## Reading layer 'rivers_buffer_glenelg_32754' from data source '/Users/mrees2/Dropbox/personal/matt/gi
## Simple feature collection with 1637 features and 13 fields
## geometry type:  MULTILINESTRING
## dimension:      XY
## bbox:           xmin: 496125.4 ymin: 5764934 xmax: 566346.2 ymax: 5812130
## CRS:            32754
```

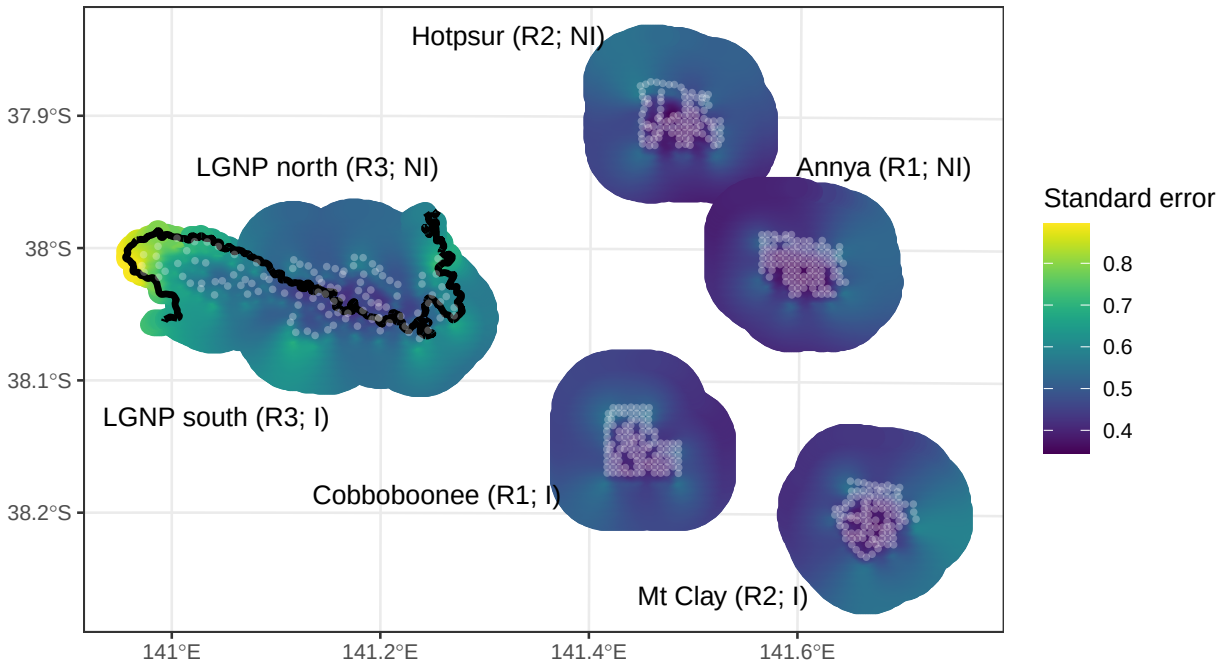

Figure 10: Standard error estimate of log fox occurrence probability derived from generalised additive models within each impact (I) and associated non-impact (NI) landscape in the Glenelg region, Australia.

5.2 Otway Region

```
##
## Family: binomial
## Link function: logit
##
## Formula:
## fox ~ year + s(x, y, by = year, bs = "ds", m = c(1, 0.5), k = 100) +
##     s(station, bs = "re") + offset(log(survey_duration))
##
## Parametric coefficients:
##              Estimate Std. Error z value            Pr(>|z|)
## (Intercept) -5.283154   0.230023 -22.968 <0.0000000000000002 ***
## year2018     0.004643   0.277696   0.017               0.987
## year2019     0.037119   0.282270   0.132               0.895
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                          edf Ref.df Chi.sq  p-value
## s(x,y):year2017  2.68844090     99  8.096 0.010597 *
## s(x,y):year2018  0.00002494     99  0.000 0.506341
## s(x,y):year2019  6.14777668     99 22.262 0.000380 ***
## s(station)      53.65519870    194 75.723 0.000116 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =   0.24   Deviance explained = 27.8%
## fREML = 763.36  Scale est. = 1         n = 513
```

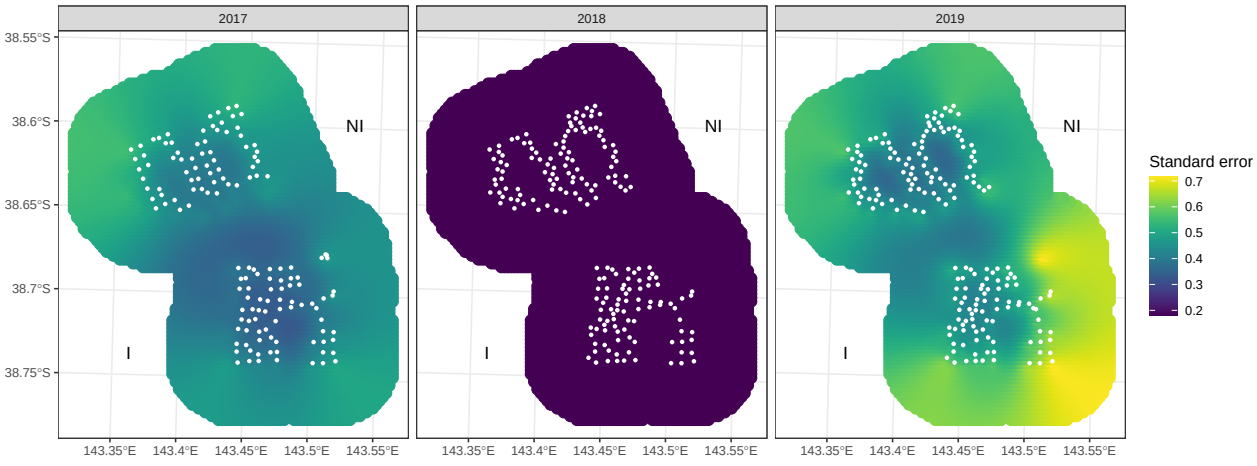

Figure 11: Standard error estimate of log fox occurrence probability derived from generalised additive models within each impact (I) and associated non-impact (NI) landscape in the Otway region, Australia.

6 Vegetation categories

We condensed the main Ecological Vegetation Class groupings (DELWP, 2020) present into three categories for each region: cleared land, heathy woodlands, lowland forests (Glenelg region only) and wet forests (Otways region only). We merged similar groups to reduce the number of categories for each region. In the Glenelg region, we merged dry forests with lowland forests. In the Otway region, we merged rainforests with wet forests, as well as merged dry forests and heathy woodlands.

A very small proportion of other Ecological Vegetation Class groupings were present in the habitat masks: riparian scrubs or swampy scrubs and woodlands, coastal scrubs grasslands and woodlands, wetlands, riverine grassy woodlands or forests, plains woodlands or forests, herb-rich woodlands. We removed these groups, and interpolated cell values from the nearest of the three vegetation categories.

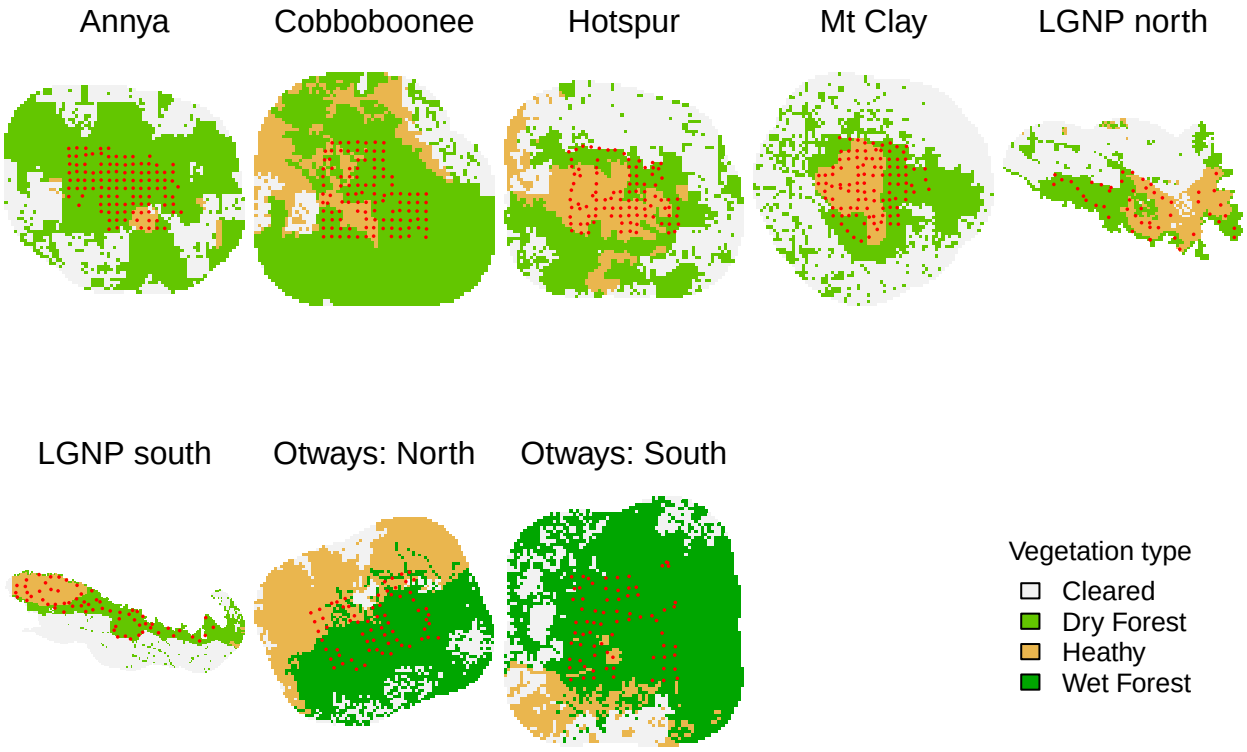

Figure 12: Condensed Ecological Vegetation Class groups used as habitat mask covariates in spatial mark-resight models.

7 Spatial mark-resight models

7.1 Glenelg region

7.1.1 Detector function fits

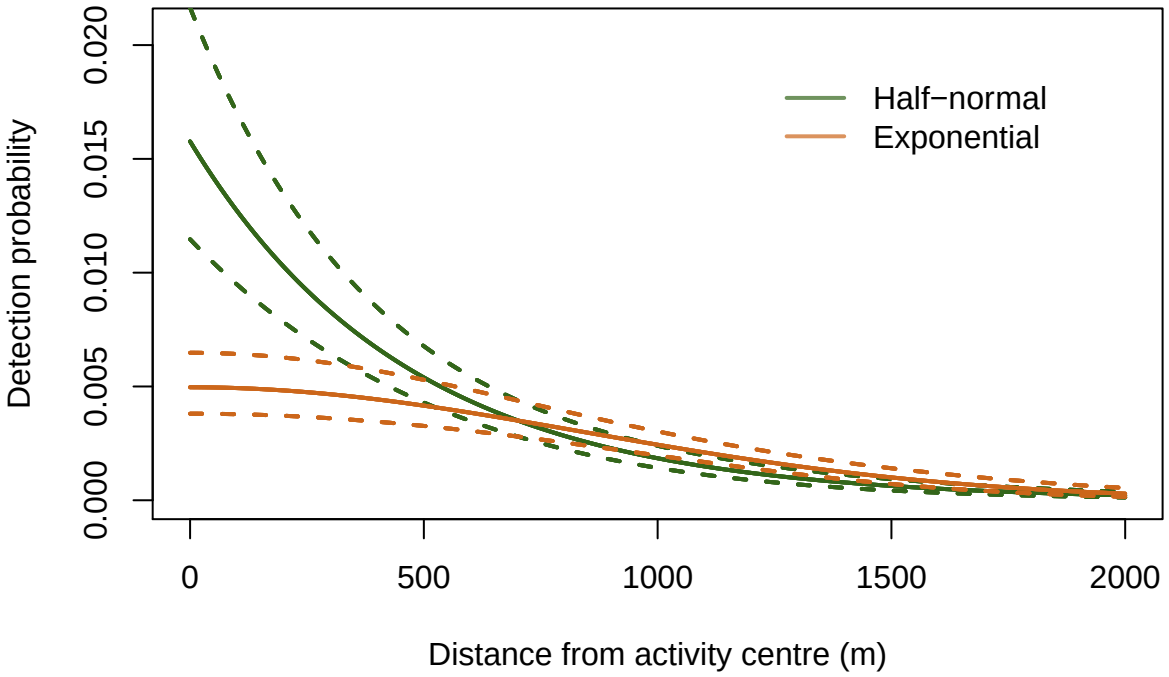

Figure 13: Detector function shapes (solid line) and 95% confidence intervals (dashed lines) tested for the Glenelg region, Australia.

Table 2: Akaike's Information Criterion values for detector functions in the Glenelg region, Australia; model set 1.

Detector function	Parameters	logLik	AIC	AICc	dAICc	AICcwt
exponential	3	-1746	3498	3498	0	1
half-normal	3	-1763	3532	3532	34.06	0

7.1.2 Candidate model fits

Table 3: Akaike's Information Criterion values adjusted for small sample size for feral cat density models in the Glenelg region; model set 2.

model	npar	logLik	AIC	AICc	dAICc	AICcwt
D~1 g0~1 sigma~1	3	-1309.93	2625.85	2626.23	0	0.3166
D~vegetation g0~1 sigma~1	5	-1307.68	2625.37	2626.35	0.116	0.2988
D~vegetation g0~T sigma~1	6	-1306.89	2625.77	2627.17	0.94	0.1979
D~1 g0~T sigma~1	4	-1309.32	2626.65	2627.29	1.057	0.1867

Table 4: Akaike's Information Criterion values adjusted for small sample size for feral cat density models in the Glenelg region; model set 3.

model	npar	logLik	AIC	AICc	dAICc	AICcwt
D~fox_occ g0~1 sigma~1	4	-1306.67	2621.33	2621.98	0	0.4918
D~fox_occ g0~fox_occ sigma~fox_occ	6	-1304.97	2621.94	2623.34	1.36	0.2492
D~s(fox_occ, k = 3) g0~1 sigma~1	5	-1306.61	2623.21	2624.2	2.219	0.1622
D~1 g0~1 sigma~1	3	-1309.93	2625.85	2626.23	4.255	0.0586
D~s(fox_occ, k = 3) g0~s(fox_occ, k = 3) sigma~s(fox_occ, k = 3)	9	-1303.41	2624.81	2627.97	5.989	0.0246
D~1 g0~fox_occ sigma~fox_occ	5	-1309.41	2628.82	2629.8	7.822	0.0098
D~1 g0~s(fox_occ, k = 3) sigma~s(fox_occ, k = 3)	7	-1307.91	2629.81	2631.71	9.73	0.0038

Table 5: Akaike's Information Criterion values adjusted for small sample size for feral cat density models in the Glenelg region; model set 4.

model	npar	logLik	AIC	AICc	dAICc	AICcwt
D~session g0~fox_occ sigma~fox_occ	10	-1297.46	2614.93	2618.86	0	0.6163
D~session g0~1 sigma~1	8	-1300.66	2617.32	2619.8	0.948	0.3837

1 - *constant*

T - *linear time trend (g0 only)*

vegetation - *modified EVC group: dry forest, heathy vegetation or cleared*

fox_occ - *fine-scale occurrence probability of foxes derived from generalised additive models*

s(fox_occ, k = 3) - *non-linear smooth of fox_occ with three knots*

session - *landscape (n = 4)*

Table 6: Feral cat density estimates per square kilometre in the Glenelg region landscapes, Australia.

Landscape	Estimate	5% CI	95% CI	Treatment	Pair
Annya	0.24	0.17	0.34	Non-impact	Replicate 1
Cobboboonee	0.6	0.4	0.88	Impact	Replicate 1
Hotspur	0.22	0.14	0.33	Non-impact	Replicate 2
Mt Clay	0.24	0.18	0.31	Impact	Replicate 2
LGNP north	0.15	0.066	0.35	Non-impact	Replicate 3
LGNP south	0.56	0.34	0.9	Impact	Replicate 3

7.2 Otway region

7.2.1 Detector function fits

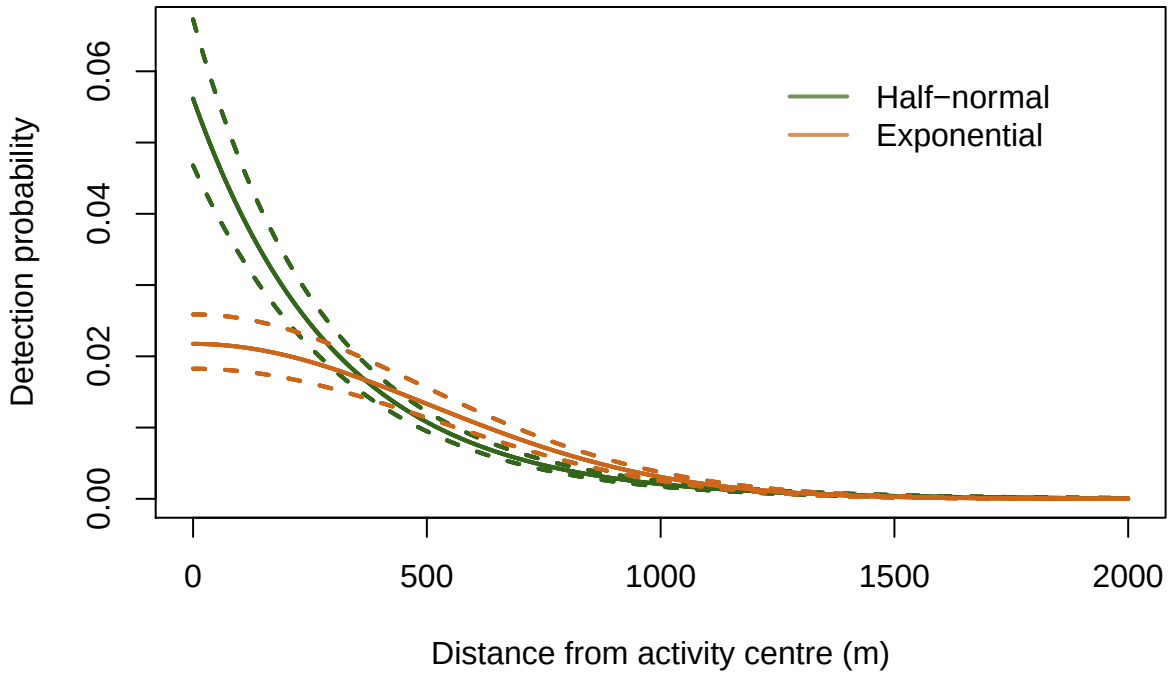

Figure 14: Detector function shapes (solid line) and 95% confidence intervals (dashed lines) tested for the Otway region, Australia.

Table 7: Akaike's Information Criterion values for detector functions in the Otway region, Australia; model set 1.

Detector function	Parameters	logLik	AIC	AICc	dAICc	AICcwt
exponential	3	-5591	11188	11188	0	1
half-normal	3	-5743	11493	11493	304.5	0

7.2.2 Candidate model fits

Table 8: Akaike's Information Criterion values adjusted for small sample size for feral cat density models in the Otway region; model set 2.

model	npar	logLik	AIC	AICc	dAICc	AICcwt
D~year g0~1 sigma~1	5	-3550.63	7111.26	7111.67	0	0.4758
D~year g0~T sigma~1	6	-3549.83	7111.67	7112.25	0.574	0.3571
D~year + vegetation g0~1 sigma~1	7	-3550.04	7114.08	7114.86	3.19	0.0965
D~year + vegetation g0~T sigma~1	8	-3549.24	7114.48	7115.49	3.815	0.0706

Table 9: Akaike's Information Criterion values adjusted for small sample size for feral cat density models in the Otway region; model set 3.

model	npar	logLik	AIC	AICc	dAICc	AICcwt
D~year + fox_occ $g0_{\text{fox_occ sigma}}$fox_occ	8	-3541.8	7099.59	7100.6	0	0.3253
D~year + s(fox_occ, k = 3) g0~s(fox_occ, k = 3) sigma~s(fox_occ, k = 3)	11	-3538.59	7099.19	7101.07	0.475	0.2565
D~year g0~s(fox_occ, k = 3) sigma~s(fox_occ, k = 3)	9	-3541.07	7100.13	7101.4	0.803	0.2177
D~year g0~fox_occ sigma~fox_occ	7	-3543.44	7100.87	7101.65	1.05	0.1924
D~year + fox_occ g0~1 sigma~1	6	-3548.26	7108.51	7109.09	8.493	0.0047
D~year + s(fox_occ, k = 3) g0~1 sigma~1	7	-3547.47	7108.94	7109.72	9.121	0.0034
D~year g0~1 sigma~1	5	-3550.63	7111.26	7111.67	11.073	0

Table 10: Akaike's Information Criterion values adjusted for small sample size for feral cat density models in the Otway region; model set 4.

model	npar	logLik	AIC	AICc	dAICc	AICcwt
D~session g0~fox_occ sigma~fox_occ	10	-3541.77	7103.55	7105.11	0	0.9868
D~session g0~1 sigma~1	8	-3548.37	7112.73	7113.74	8.631	0.0132

1 *- constant*

T *- linear time trend (g0 only)*

vegetation *- modified EVC group: wet forest, heathy vegetation or cleared*

year *- year of deployment (2017-19)*

fox_occ *- fine-scale occurrence probability of foxes derived from generalised additive models*

s(fox_occ, k = 3) *- non-linear smooth of fox_occ with three knots*

session *- landscape (n = 4)*

Table 11: Feral cat density estimates per square kilometre in the Otway region landscapes, Australia.

Landscape	Estimate	5% CI	95% CI	Treatment	Pair
north 2017	1	0.74	1.3	Non-impact	2017
south 2017	0.74	0.52	1	Impact	2017
north 2018	0.81	0.64	1	Non-impact	2018
south 2018	0.82	0.63	1.1	Impact	2018
north 2019	0.73	0.55	0.95	Non-impact	2019
south 2019	0.98	0.76	1.3	Impact	2019

8 Session information

R version 3.6.3 (2020-02-29)

Platform: x86_64-apple-darwin15.6.0 (64-bit)

locale: en_AU.UTF-8||en_AU.UTF-8||en_AU.UTF-8||C||en_AU.UTF-8||en_AU.UTF-8

attached base packages: *stats*, *graphics*, *grDevices*, *utils*, *datasets*, *methods* and *base*

other attached packages: *terra(v.1.1-4)*, *sp(v.1.4-5)*, *sf(v.0.9-6)*, *viridis(v.0.5.1)*, *viridisLite(v.0.4.0)*, *patchwork(v.1.0.1)*, *gratia(v.0.6.0)*, *pander(v.0.6.3)*, *RColorBrewer(v.1.1-2)*, *camtrapR(v.2.0.3)*, *mgcv(v.1.8-33)*, *nlme(v.3.1-144)*, *secr(v.4.4.5)*, *forcats(v.0.5.0)*, *stringr(v.1.4.0)*, *dplyr(v.1.0.2)*, *purrr(v.0.3.4)*, *readr(v.1.3.1)*, *tidyr(v.1.0.0)*, *tibble(v.3.1.2)*, *ggplot2(v.3.3.3)*, *tidyverse(v.1.3.0)* and *bookdown(v.0.21)*

loaded via a namespace (and not attached): *fs(v.1.5.0)*, *overlap(v.0.3.2)*, *lubridate(v.1.7.10)*, *httr(v.1.4.2)*, *tools(v.3.6.3)*, *RcppNumerical(v.0.4-0)*, *backports(v.1.2.1)*, *rgdal(v.1.4-7)*, *utf8(v.1.2.2)*, *R6(v.2.5.0)*, *KernSmooth(v.2.23-16)*, *DBI(v.1.1.1)*, *colorspace(v.2.0-1)*, *raster(v.3.4-10)*, *withr(v.2.4.2)*, *tidyselect(v.1.1.0)*, *gridExtra(v.2.3)*, *compiler(v.3.6.3)*, *cli(v.3.0.1)*, *rvest(v.1.0.0)*, *xml2(v.1.3.2)*, *labeling(v.0.4.2)*, *scales(v.1.1.1)*, *classInt(v.0.4-3)*, *mvnfast(v.0.2.5)*, *digest(v.0.6.27)*, *rmarkdown(v.2.7)*, *pkgconfig(v.2.0.3)*, *htmltools(v.0.5.1.1)*, *highr(v.0.8)*, *dbplyr(v.1.4.2)*, *rlang(v.0.4.11)*, *readxl(v.1.3.1)*, *rstudioapi(v.0.13)*, *farver(v.2.1.0)*, *generics(v.0.1.0)*, *jsonlite(v.1.7.2)*, *magrittr(v.2.0.1)*, *Matrix(v.1.2-18)*, *Rcpp(v.1.0.7)*, *munsell(v.0.5.0)*, *fansi(v.0.5.0)*, *abind(v.1.4-5)*, *lifecycle(v.1.0.0)*, *stringi(v.1.5.3)*, *yaml(v.2.2.1)*, *MASS(v.7.3-51.5)*, *grid(v.3.6.3)*, *parallel(v.3.6.3)*, *crayon(v.1.4.1)*, *lattice(v.0.20-38)*, *haven(v.2.2.0)*, *splines(v.3.6.3)*, *hms(v.0.5.2)*, *knitr(v.1.31)*, *pillar(v.1.6.1)*, *codetools(v.0.2-16)*, *reprex(v.0.3.0)*, *glue(v.1.4.2)*, *evaluate(v.0.14)*, *data.table(v.1.12.6)*, *RcppParallel(v.5.1.4)*, *modelr(v.0.1.6)*, *vctrs(v.0.3.8)*, *cellranger(v.1.1.0)*, *gtable(v.0.3.0)*, *assertthat(v.0.2.1)*, *xfun(v.0.22)*, *broom(v.0.7.9)*, *e1071(v.1.7-2)*, *class(v.7.3-15)*, *units(v.0.6-5)* and *ellipsis(v.0.3.2)*

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