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Wildlife Research

Supplementary Material

Estimating and validating koala *Phascolarctos cinereus* density estimates from acoustic arrays using spatial count modelling

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Appendix A- Home range size and calculations for the σ priors

Home range size estimates for koala were based on expert opinion and recent literature. Within Upper Nepean SCA, and based on recent tracking data, male koala home range size is considered to be ~24 ha for a 2-week period in October or ~125 ha overall home range, both assuming medium quality habitat (L. Wilmott, *unpubl. data*). Within Canyonleigh male koala mean home range size is considered to be ~493 ha (104-863 ha range) (Wilmott et al. *unpublished data*). Male koala home range sizes in Bongil Bongil National Park are considered to be an order of magnitude smaller, ranging from 10-80 ha, mean 40 ha (S. Miller, *unpublished data*). Within Murrah Flora Reserve male koala home range size ranges from 40-170 ha, mean 90 ha (Jurskis and Potter, 1997). The smallest male koala home range sizes are within Gunnedah, ranging from 4-53 ha, mean 22 ha (Mella et al., *unpublished data*).

Since detections are for male koalas as these are the individuals calling, we considered the range in male home range sizes to inform our σ priors. We also considered individual calls to have a detection distance of 100-300 m (Hagens et al. 2018; Law et al. 2020). We calculated the home range of σ following Chandler & Royle (2013) and assuming a chi-squared distribution with 2 degrees of freedom.

R code calculations for the calculations for the σ priors

```
###--- Function to determine value for density prior
# x = home range (ha), y = 1 unit grid spacing
# dtn_lower = lower distance koala bellow travels
# dtn_higher = higher distance koala bellow travels
informed_sigma.function <- function(x, y=100, dtn_lower=100, dtn_upper=300){

  dtn_dist <- sqrt(x/pi*10000)

  dtn_dist_lower <- (dtn_dist + dtn_lower)^2*pi / 10000
  dtn_dist_upper <- (dtn_dist + dtn_upper)^2*pi / 10000

  # Following Royle et. al (2011), and assuming a
  # chi-squared distribution with 2 degrees of freedom,
  # the range of sigma is given by

  sigma_lower <- sqrt(dtn_dist_lower*10000/pi)/sqrt(5.99)
  sigma_higher <- sqrt(dtn_dist_upper*10000/pi)/sqrt(5.99)

  y_lower <- sigma_lower/y # 0.97
  y_upper <- sigma_higher/y # 2.99

  prior_density <- c(y_lower, y_upper)

  return(prior_density)
}

### Considering all koala home ranges,
# create a weakly informative prior (WIA1) based on the range of home range sizes: 4-863
# HR_004 = 0.8696322 1.6868100; HR_863 = 7.180590 7.997768
# want density between 0.8696322 and 7.997768
qgamma(c(0.05,0.5,0.95),4,1)  # 1.366318 3.672061 7.753657

## home ranges between 4-863 ha
## WIA1 = dgamma = 4,1
curve(dgamma(x,4,1), col='black',xlim=c(0,10), ylim=c(0,1.8))
```

Home range (HR) estimates for the **Upper Nepean** study area
 # 24-125 ha HR = 1.54 and 3.80
 # 24 ha HR = 1.54 and 2.35
 # 125 ha HR = 2.99 and 3.80

qgamma(c(0.001,0.5,0.999),15,6) # 0.9656626 2.4446693 4.9752554 - variable HR from 24-125
qgamma(c(0.001,0.5,0.999),50,25) # 1.301213 2.311149 3.743898 - tight HR centred on 24
qgamma(c(0.001,0.5,0.999),70,21) # 2.236325 3.317474 4.701209 - tight HR centred on 125

curve(dgamma(x,15,6), col='black',xlim=c(0,5), ylim=c(0,2)) ## HR between 24-125 ha
curve(dgamma(x,50,25), col='red', add=TRUE) ## tight HR centred on 24
curve(dgamma(x,70,21), col='green', add=TRUE) ## tight HR centred on 125

Home range (HR) estimates for the **Canyonleigh** study area

weakly informative 104-863; WIC2 = dgamma = 10,2
HR_104 = 2.759457 3.576635; HR_863 = 7.180590 7.997768;
want density between 2.759457 and 7.997768
qgamma(c(0.05,0.5,0.95),10,2) # 2.712703 4.834357 7.852608
home ranges between 104-863 ha
curve(dgamma(x,10,2), col='red', add = TRUE)

strongly informative 493; SIC1 = dgamma = 60,10
HR_493 = 5.526999 6.344177
want density between 5.526999 and 6.344177
mean(HR_493) # peak at 5.935588
qgamma(c(0.05,0.5,0.95),60,10) # 4.785232 5.966700 7.328368
tight home range centred on 493
curve(dgamma(x,60,10), col='blue', add=TRUE)

Home range (HR) estimates for the **Bongil Bongil** study area

weakly informative 10-90; WIB2 = dgamma = 10,4.6
HR_010 = 1.137562 1.954740; HR_090 = 2.595509 3.412687;
want density between 1.137562 and 3.412687
qgamma(c(0.05,0.5,0.95),10,4.6) # 1.179436 2.101894 3.414177
home ranges between 10-90 ha
curve(dgamma(x,10,4.6), col='red', add = TRUE)

strongly informative 40; SIB1 = dgamma = 60,27
HR_040 = 1.866536 2.683713
want density between 1.866536 and 2.683713
mean(HR_040) # peak at 2.275125
qgamma(c(0.05,0.5,0.95),60,27) # 1.772308 2.209889 2.714210
tight home range centred on 40
curve(dgamma(x,60,27), col='blue', add=TRUE)
Home range (HR) estimates for the **Murrah** study area

weakly informative 40-170; WIM2 = dgamma = 10,3.5

```
# HR_040 = 1.866536 2.683713; HR_170 = 3.414223 4.231401;
# want density between 1.866536 and 4.231401
qgamma(c(0.05,0.5,0.95),10,3.5)  # 1.550116 2.762490 4.487205
## home ranges between 40-170 ha
curve(dgamma(x,10,3.5), col='red', add = TRUE)

# strongly informative 90; SIM1 = dgamma = 60,20
# HR_090 = 2.595509 3.412687
# want density between 2.595509 and 3.412687
mean(HR_090) # peak at 3.004098
qgamma(c(0.05,0.5,0.95),60,20)  # 2.392616 2.983350 3.664184
## tight home ranges centred on 90
curve(dgamma(x,60,20), col='blue', add=TRUE)
```

Home range (HR) estimates for the **Gunnedah** study area

```
# weakly informative 4-53; WIG2 = dgamma = 12,7
# HR_004 = 0.8696322 1.6868100; HR_053 = 2.086812 2.903989;
# want density between 0.8696322 and 2.903989
qgamma(c(0.05,0.5,0.95),12,7)  # 0.9891732 1.6669090 2.6010735
## home ranges between 4-53 ha
curve(dgamma(x,12,7), col='red', add = TRUE)

# strongly informative 22; SIG1 = dgamma = 60,32
# HR_022 = 1.489831 2.307009
# want density between 1.489831 and 2.307009
mean(HR_022) # peak at 1.89842
qgamma(c(0.05,0.5,0.95),60,32)  #
## tight home range centred on 22
curve(dgamma(x,60,32), col='blue', add=TRUE)
```

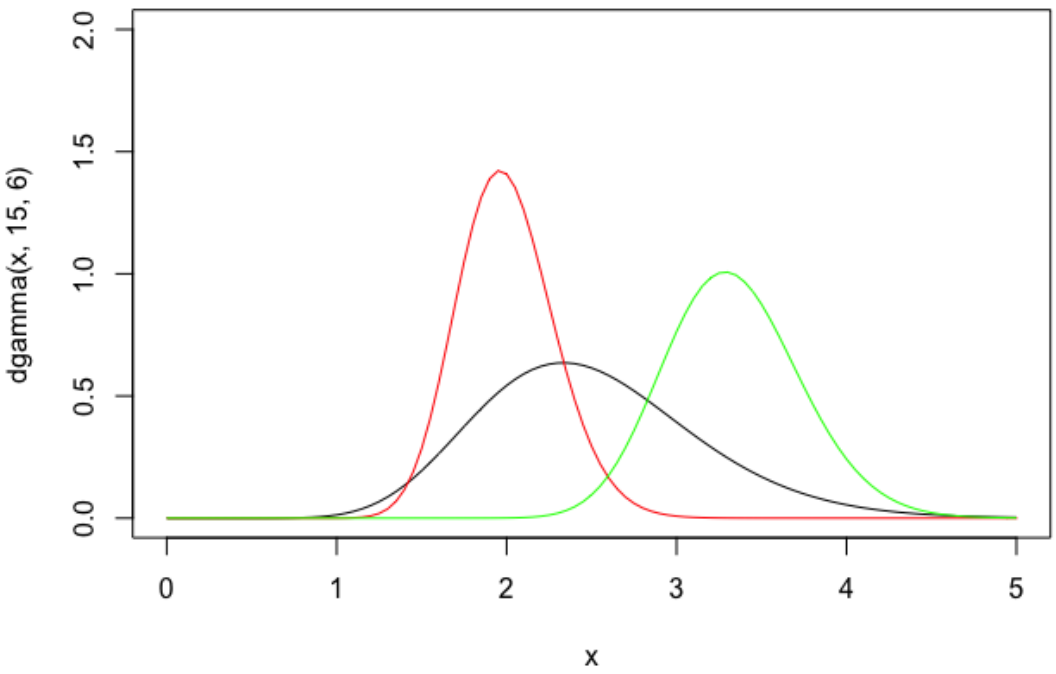

Figure A1. Gamma distribution for informative σ priors for the **Upper Nepean** study area, with most of the density between home range equivalents of 24-125 ha (black; WIU1), or centred on 24 ha (red; SIU1), and 125 ha (green; SIU2).

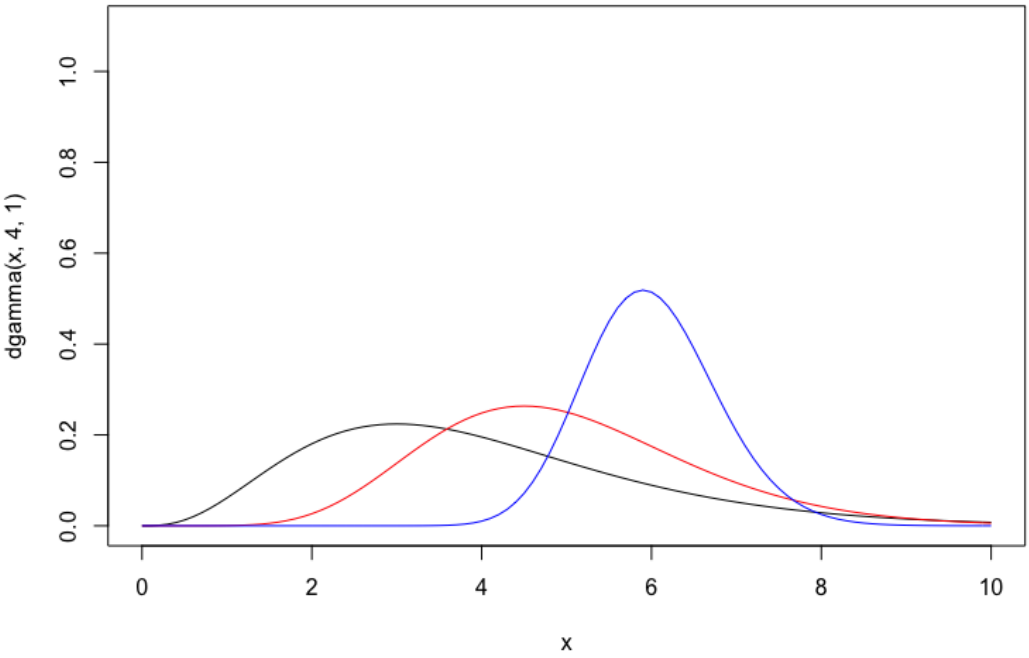

Figure A2. Gamma distribution for informative σ priors for the **Canyonleigh** study area, with most of the density between home range equivalents of 4-863 ha (black; WIA1), 104-863 ha (red; WIC2), and centred on 493 ha (blue; SIC1).

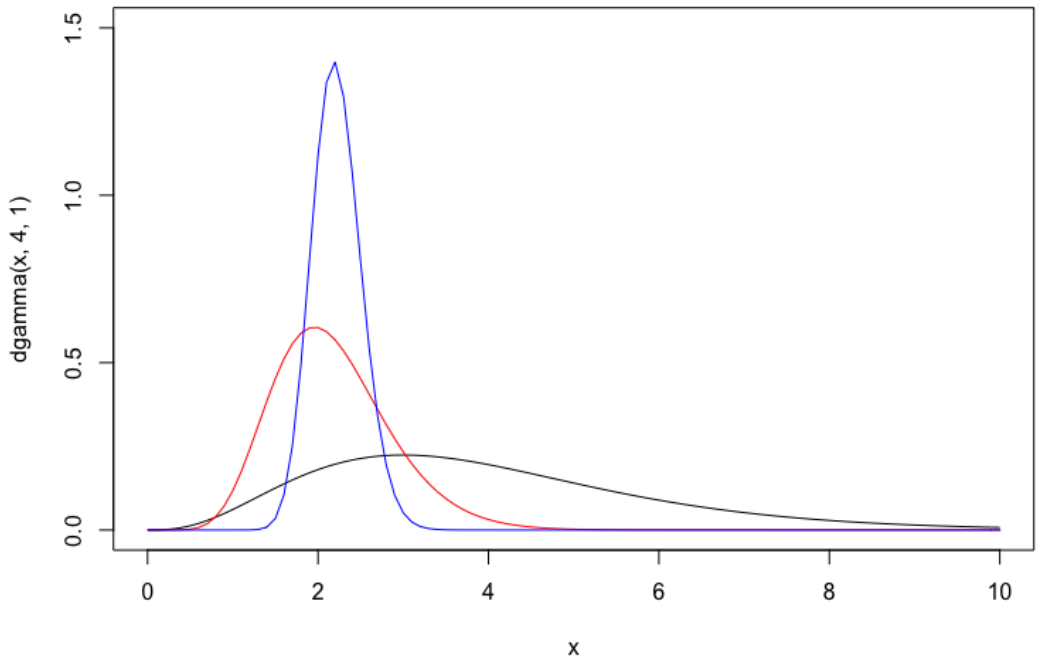

Figure A3. Gamma distribution for informative σ priors for the **Bongil Bongil** study area, with most of the density between home range equivalents of 4-863 ha (black; WIA1), 10-90 ha (red; WIB2), and centred on 40 ha (blue; SIB1).

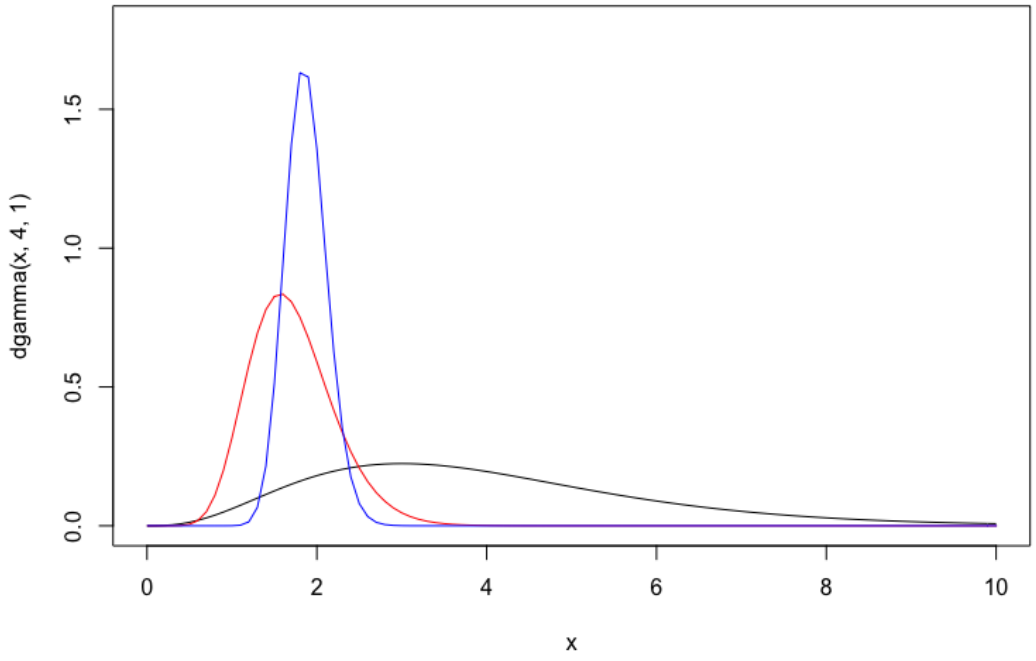

Figure A4. Gamma distribution for informative σ priors for the **Gunnedah** study area, with most of the density between home range equivalents of 4-863 ha (black; WIA1), 4-53 ha (red; WIG2), and centred on 22 ha (blue; SIG1).

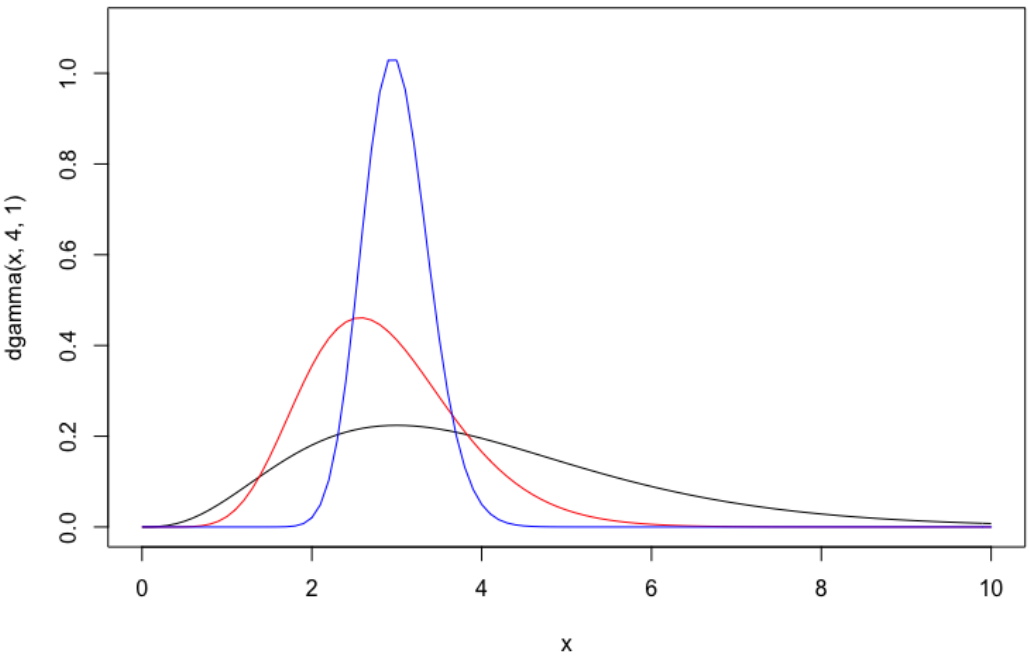

Figure A5. Gamma distribution for informative σ priors for the **Murrah** study area, with most of the density between home range equivalents of 4-863 ha (black; WIA1), 40-170 ha (red; WIM2), and centred on 90 ha (blue; SIM1).

Spatial Count Model Output – Results

Upper Nepean

Table A1. Koala parameter estimates for spatial count models using acoustic detections of male koalas in **Upper Nepean** in spring (31 October to 14 November) 2017. Median and mean estimates, the 2.5% and 97.5% Bayesian Credible Intervals, coefficient of variation (CV; mean divided by the standard deviation) and the Gelman-Rubin statistic ($\widehat{\boldsymbol{R}}$) are provided. Models differed only in the prior on σ, the spatial scale parameter – UIU1 = uninformative prior, WIU1 = weakly informative prior (24-125 ha home range), SIU1 and SIU2 = strongly informative priors centred on 24 ha and 125 ha home ranges, respectively. The strongly informative prior model estimates are highlighted in grey.

	Model	Median	Mean	2.5%	97.5%	CV	$\hat{R}$
Density							
	UIU1	0.05	0.07	0.02	0.20	0.71	1.32
	WIU1	0.04	0.04	0.01	0.13	0.62	1.02
	SIU1	0.07	0.07	0.03	0.14	0.43	1.01
	SIU2	0.02	0.03	0.01	0.05	0.32	1.01
σ							
	UIU1	2.22	2.19	1.12	3.43	0.31	1.35
	WIU1	2.59	2.61	1.52	3.57	0.19	1.03
	SIU1	1.99	1.96	1.36	2.57	0.17	1.01
	SIU2	3.20	3.18	2.60	3.67	0.08	1.00
λ_0							
	UIU1	6.80	7.11	4.45	10.85	0.23	1.03
	WIU1	6.96	7.24	4.46	11.35	0.25	1.02
	SIU1	6.95	7.18	4.57	10.96	0.24	1.01
	SIU2	7.19	7.37	4.32	11.45	0.24	1.01
ψ							
	UIU1	0.25	0.35	0.09	0.92	0.71	1.32
	WIU1	0.18	0.21	0.06	0.61	0.62	1.02
	SIU1	0.31	0.35	0.15	0.69	0.43	1.01
	SIU2	0.11	0.12	0.06	0.22	0.34	1.01

Canyonleigh

Table A2. Koala parameter estimates for spatial count models using acoustic detections of male koalas in **Canyonleigh** in spring (23-29 October) 2019. Median and mean estimates, the 2.5% and 97.5% Bayesian Credible Intervals, coefficient of variation (CV; mean divided by the standard deviation) and the Gelman-Rubin statistic ($\widehat{\boldsymbol{R}}$) are provided. Models differed only in the prior on σ, the spatial scale parameter – UIC1 = uninformative prior, WIA1 = weakly informative regional prior (4-863 ha home range), weakly informative study area prior = WIC1 (104-863 ha home range), and strongly informative study area prior = SIC1 (493 ha home range). The strongly informative prior model estimates are discussed in the manuscript and highlighted in grey.

	Model	Median	Mean	2.5%	97.5%	CV	$\hat{R}$
Density							
	UIC1	0.06	0.09	0.02	0.37	0.85	1.11
	WIA1	0.05	0.06	0.02	0.17	0.64	1.00
	WIC1	0.04	0.04	0.01	0.11	0.54	1.01
	SIC1	0.01	0.01	0.01	0.03	0.46	1.00
σ							
	UIC1	2.44	2.40	1.10	3.38	0.23	1.05
	WIA1	2.58	2.57	1.54	3.51	0.19	1.00
	WIC1	2.79	2.82	2.07	3.80	0.16	1.00
	SIC1	4.24	4.24	3.32	5.10	0.11	1.01
λ_0							
	UIC1	2.19	2.39	1.26	4.40	0.35	1.31
	WIA1	2.60	2.72	1.27	4.72	0.33	1.00
	WIC1	2.92	3.06	1.47	5.71	0.35	1.01
	SIC1	5.28	5.46	2.76	9.91	0.34	1.00
ψ							
	UIC1	0.15	0.20	0.05	0.86	0.85	1.11
	WIA1	0.12	0.15	0.04	0.40	0.64	1.00
	WIC1	0.09	0.11	0.03	0.25	0.55	1.01
	SIC1	0.03	0.03	0.01	0.07	0.49	1.00

Bongil Bongil

Table A3. Koala parameter estimates for spatial count models using acoustic detections of male koalas in **Bongil Bongil** in spring (21-31 October) 2019. Median and mean estimates, the 2.5% and 97.5% Bayesian Credible Intervals, coefficient of variation (CV; mean divided by the standard deviation) and the Gelman-Rubin statistic ($\widehat{\boldsymbol{R}}$) are provided. Models differed only in the prior on σ, the spatial scale parameter – UIB1 = uninformative prior, WIA1 = weakly informative regional prior (4-863 ha home range), weakly informative study area prior = WIB1 (10-80 ha home range), and strongly informative study area prior = SIB1 (40 ha home range). The strongly informative prior model estimates are discussed in the manuscript and highlighted in grey.

	Model	Median	Mean	2.5%	97.5%	CV	$\hat{R}$
Density							
	UIB1	0.07	0.10	0.03	0.39	0.82	1.09
	WIA1	0.06	0.07	0.03	0.21	0.66	1.02
	WIB1	0.06	0.07	0.03	0.18	0.59	1.01
	SIB1	0.04	0.05	0.02	0.09	0.38	1.01
σ							
	UIB1	1.52	1.45	0.61	2.06	0.27	1.05
	WIA1	1.66	1.62	0.92	2.09	0.18	1.02
	WIB1	1.63	1.62	1.07	2.10	0.16	1.00
	SIB1	1.89	1.90	1.56	2.27	0.09	1.00
λ_0							
	UIB1	2.08	2.19	1.17	4.01	0.31	1.00
	WIA1	2.07	2.12	1.18	3.47	0.27	1.00
	WIB1	2.00	2.06	1.15	3.41	0.28	1.01
	SIB1	2.14	2.23	1.27	3.76	0.28	1.01
ψ							
	UIB1	0.17	0.23	0.06	0.87	0.82	1.09
	WIA1	0.13	0.17	0.06	0.47	0.66	1.02
	WIB1	0.14	0.16	0.06	0.41	0.59	1.00
	SIB1	0.10	0.10	0.04	0.20	0.39	1.01

Gunnedah

Table D4. Koala parameter estimates for spatial count models using acoustic detections of male koalas in **Gunnedah** in spring (25 October – 1 November) 2019. Median and mean estimates, the 2.5% and 97.5% Bayesian Credible Intervals, coefficient of variation (CV; mean divided by the standard deviation) and the Gelman-Rubin statistic ($\widehat{\boldsymbol{R}}$) are provided. Models differed only in the prior on σ, the spatial scale parameter – UIG1 = uninformative prior, WIA1 = weakly informative regional prior (4-863 ha home range), weakly informative study area prior = WIG1 (4-53 ha home range), and strongly informative study area prior = SIG1 (22 ha home range). Note the high values in the 97.5% Bayesian Credible Interval column, indicating these models did not converge.

	Model	Median	Mean	2.5%	97.5%	CV	$\hat{R}$
Density							
	UIG1	0.28	0.27	0.09	0.40	0.32	1.01
	WIA1	0.22	0.22	0.05	0.39	0.47	1.03
	WIG1	0.31	0.30	0.14	0.40	0.23	1.01
	SIG1	0.33	0.32	0.18	0.41	0.20	1.03
σ							
	UIG1	2.30	2.36	1.77	3.29	0.16	1.03
	WIA1	2.46	2.62	1.73	4.99	0.28	1.12
	WIG1	2.07	2.10	1.63	2.86	0.14	1.01
	SIG1	1.99	2.00	1.65	2.35	0.09	1.02
λ_0							
	UIG1	2.44	2.60	1.34	5.49	0.38	1.09
	WIA1	2.69	2.90	1.48	5.81	0.37	1.21
	WIG1	2.67	2.74	1.54	4.41	0.27	1.02
	SIG1	2.72	2.83	1.83	4.41	0.24	1.03
ψ							
	UIG1	0.67	0.65	0.22	0.98	0.32	1.01
	WIA1	0.53	0.53	0.13	0.96	0.47	1.03
	WIG1	0.76	0.74	0.35	0.99	0.23	1.01
	SIG1	0.80	0.77	0.43	0.99	0.20	1.03

Murrah

Table A5. Koala parameter estimates for spatial count models using acoustic detections of male koalas in **Murrah** in spring (27 October – 2 November) 2019. Median and mean estimates, the 2.5% and 97.5% Bayesian Credible Intervals, coefficient of variation (CV; mean divided by the standard deviation) and the Gelman-Rubin statistic ($\widehat{\boldsymbol{R}}$) are provided. Models differed only in the prior on σ, the spatial scale parameter – UIM1 = uninformative prior, WIA1 = weakly informative regional prior (4-863 ha home range), weakly informative study area prior = WIM1 (40-170 ha home range), and strongly informative study area prior = SIM1 (90 ha home range). The strongly informative prior model estimates are discussed in the manuscript and highlighted in grey.

	Model	Median	Mean	2.5%	97.5%	CV	$\hat{R}$
Density							
	UIM1	0.06	0.10	0.03	0.42	1.04	1.00
	WIA1	0.05	0.09	0.03	0.37	0.97	1.19
	WIM1	0.04	0.05	0.03	0.10	0.42	1.02
	SIM1	0.04	0.04	0.02	0.06	0.27	1.00
σ							
	UIM1	1.71	1.57	0.53	2.22	0.30	1.01
	WIA1	1.75	1.61	0.54	2.21	0.28	1.09
	WIM1	1.88	1.85	1.32	2.27	0.13	1.00
	SIM1	2.16	2.16	1.85	2.49	0.07	1.00
λ_0							
	UIM1	4.63	4.76	2.79	7.81	0.26	1.00
	WIA1	4.72	4.90	2.85	8.21	0.28	1.01
	WIM1	4.60	4.67	2.90	6.91	0.22	1.00
	SIM1	4.48	4.49	2.89	6.11	0.18	1.00
ψ							
	UIM1	0.11	0.19	0.05	0.81	1.03	1.00
	WIA1	0.11	0.17	0.05	0.71	0.96	1.19
	WIM1	0.09	0.10	0.05	0.20	0.44	1.01
	SIM1	0.07	0.07	0.04	0.12	0.31	1.00

Literature Cited

Chandler, R.B., Royle, J.A.A., 2013. Spatially explicit models for inference about density in unmarked or partially marked populations. Ann. Appl. Stat. 7, 936–954. https://doi.org/10.1214/12-AOAS610

Ellis, W.A.H., Melzer, A., Bercovitch, F.B., 2009. Spatiotemporal dynamics of habitat use by koalas: the checkerboard model. Behav. Ecol. Sociobiol. 63, 1181–1188. https://doi.org/10.1007/s00265-009-0761-2

Hagens S.V., Rendall A.R., Whisson D.A., 2018. Passive acoustic surveys for predicting species' distributions: Optimising detection probability. PLoS ONE **13**:e0199396.

Jurskis, V., Potter, M., 1997. Koala surveys, ecology and conservation at Eden. State Forests of New South Wales Research Paper No. 34., State Forests of New South Wales. Sydney.

Law B., Gonsalves L., Bilney R., Peterie J., Pietsch R., Roe P., Truskinger A., 2020. Using passive acoustic recording and automated call identification to survey koalas in the southern forests of New South Wales. Australian Zoologist **40**:477–486.

Matthews, A., Lunney, D., Gresser, S., Maitz, W., 2016. Movement patterns of koalas in remnant forest after fire. Aust. Mammal. 38, 91. https://doi.org/10.1071/AM14010