Efficient discretization of movement kernels for spatiotemporal capture–recapture. Journal of Agricultural, Biological and Environmental Statistics

Supplementary material

Appendix A: R code for simulations

Simulations to compare full and sparse kernels were detailed in the main text. This appendix provides R code (R Core Team 2021) for running the simulations with package 'openCR' (Efford 2021). Detailed results are provided as a .csv file elsewhere in the supplementary material.

References

Efford MG (2021) openCR: Open population capture–recapture models. R package version 2.1.0. https://CRAN.R-project.org/package=openCR

R Core Team (2021) R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. https://www.R-project.org/.


```
#-----------------------------------------------------------------------------------
library(openCR)

# build dataframe of scenarios
scen <- expand.grid(sparsekernel = c(FALSE,TRUE), median = c(30,60),
    movemodel = c('BVN','BVE'), kernelradius = c(10,20),
    nsessions = 5, move.a = NA, stringsAsFactors = FALSE)
```

```
# matchscale() is openCR function that finds the scale parameter
# giving distribution with the required quantile (defaults to median p=0.5)
scen$move.a[scen$movemodel=='BVN' & scen$median==30] <- matchscale('BVN', 30)
scen$move.a[scen$movemodel=='BVN' & scen$median==60] <- matchscale('BVN', 60)
scen$move.a[scen$movemodel=='BVE' & scen$median==30] <- matchscale('BVE', 30)
scen$move.a[scen$movemodel=='BVE' & scen$median==60] <- matchscale('BVE', 60)

# review scenarios
scen
#    sparsekernel median movemodel kernelradius nsessions   move.a
# 1         FALSE     30       BVN           10         5 25.47966
# 2          TRUE     30       BVN           10         5 25.47966
# 3         FALSE     60       BVN           10         5 50.95931
# 4          TRUE     60       BVN           10         5 50.95931
# 5         FALSE     30       BVE           10         5 17.87475
# 6          TRUE     30       BVE           10         5 17.87475
# 7         FALSE     60       BVE           10         5 35.74943
# 8          TRUE     60       BVE           10         5 35.74943
# 9         FALSE     30       BVN           20         5 25.47966
# 10         TRUE     30       BVN           20         5 25.47966
# 11        FALSE     60       BVN           20         5 50.95931
# 12         TRUE     60       BVN           20         5 50.95931
# 13        FALSE     30       BVE           20         5 17.87475
# 14         TRUE     30       BVE           20         5 17.87475
# 15        FALSE     60       BVE           20         5 35.74943
# 16         TRUE     60       BVE           20         5 35.74943

# set up simulations
nrepl <- 100
setNumThreads(20)
grid <- make.grid(nx = 8, ny = 8, spacing = 30, detector = 'multi')
msk <- make.mask(grid, buffer = 210, spacing = 15)   # rectangular

# run each scenario, saving results to a file
# each output file contains a list with one component per replicate
for (s in 1:16) {
    set.seed(1235)
    predicted <- list()
```

```
    for (r in 1:nrepl) {
        turnover <- list(lambda = 1, phi = 1,
            movemodel = scen$movemodel[s],
            move.a = scen$move.a[s],
            move.b = scen$move.b[s])
        pop <- sim.popn(core = grid,
            Nbuffer = 200,
            buffer = 210,
            details = turnover,
            nsessions = scen$nsessions[s],
            Ndist = 'fixed')
        ch <- sim.capthist(grid, popn = pop, detectfn = 'HHN',
            detectpar = list(lambda0 = 0.1, sigma = 30),
            noccasions = 5, renumber = FALSE)
        fit <- openCR.fit(ch,
            type = 'PLBsecrf',
            fixed = list(phi = 1, f = 0),
            movementmodel = scen$movemodel[s],
            kernelradius = scen$kernelradius[s],
            sparsekernel = scen$sparsekernel[s],
            mask = msk, trace = TRUE)
        predicted[[r]] <- predict(fit)
    }
    saveRDS(predicted, file = paste0('simulated sparse vs full 100 ', s, '.RDS'))
}
#-----------------------------------------------------------------------------------
```

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Appendix B: Case studies

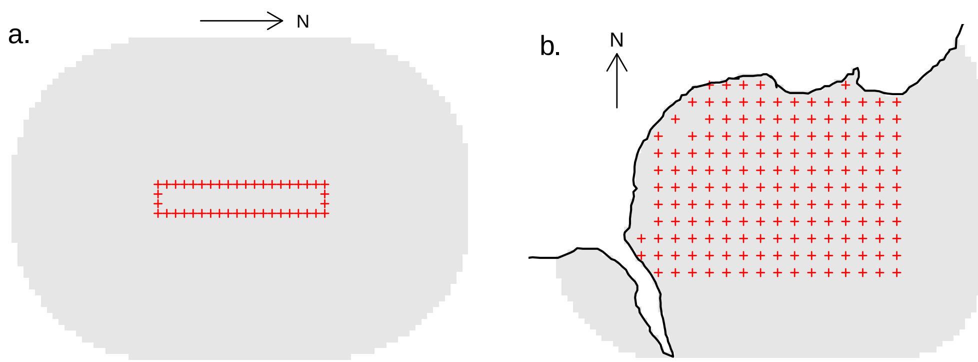

Figure S1: Configuration of study areas. (a) Ovenbird study: array of 44 mist nets at 30-m spacing; shading indicates 500-m buffer, (b) Brushtail possum study: array of 167 cage traps at 30-m spacing; shading indicates 150-m buffer in forest, truncated by shingle riverbed to the north and west.

Ovenbird

The ovenbird (*Seiurus aurocapilla*) is a migratory ground-nesting warbler. The data are from a multi-species banding study over the 2005–2009 breeding seasons on the Patuxent Research Refuge, Maryland, USA. Ovenbirds were mistnetted and banded each year for 9 or 10 days at 44 points spaced 30 m apart on a rectangular loop

(Dawson and Efford 2009) (data in Efford 2021 and Dawson and Efford 2022). About 20 ovenbirds were caught each year (Table S1a). Mist nets were treated for the analysis as 'binary proximity detectors', i.e., the presence or absence of each detected bird was recorded at each net on each day (Efford et al. 2009). The habitat mesh comprised points on a 20-m grid within 500 m of any trap (Fig. S1).

Brushtail possum

The brushtail possum (*Trichosurus vulpecula*) is invasive in New Zealand forests; adult possums occupy a stable home range year round except for occasional excursions (Ward 1978). We use the 1996 and 1997 data from a long-term trapping study in the Orongorongo Valley near Wellington, New Zealand (Efford and Cowan 2004) (data in Efford 2021). These were years of unusually high and declining possum density. Possums were trapped on an array of 167 cage traps at 30-m spacing and individually ear marked for 5 nights in February, June and September of each year. The brushtail possum dataset was an order of magnitude larger than the ovenbird dataset (Table S1b). The habitat mesh comprised points on a 10-m grid within 150 m of a trap, excluding points in a shingle river bed that bounded the detector array to the north and west. The traps caught a maximum of one possum at a time, with rare exceptions. No probability model is available for the single-catch scenario. A 'multi-catch' probability model (allowing each animal to be caught in only one trap per occasion, but multiple animals per trap) has been found adequate for density estimation in closed-population SECR, although the baseline detection rate is underestimated (Efford et al. 2009). That model was used here.

References

Dawson DK, Efford MG (2009) Bird population density estimated from acoustic signals. Journal of Applied Ecology 46:1201–1209.

Dawson DK, Efford MG (2022) Ovenbird mist-netting dataset. Zenodo. https://doi.org/10.5281/zenodo.6622163

Efford MG (1998). Demographic consequences of sex-biased dispersal in a population of brushtail possums. Journal of Animal Ecology 67:503–517.

Efford MG (2021) secr: spatially explicit capture-recapture models. R package version 4.4.5. https://CRAN.R-project.org/package=secr

Efford MG, Cowan PE (2004) Long-term population trend of *Trichosurus vulpecula* in the Orongorongo Valley, New Zealand. In: Goldingay RL, Jackson SM (eds) The biology of Australian possums and gliders. Surrey Beatty and Sons, Chipping Norton, pp 471–483.

Efford MG, Borchers DL, Byrom AE (2009) Density estimation by spatially explicit capture–recapture: likelihood-based methods. In: Thomson, DL, Cooch EG, Conroy MJ (eds) Modeling demographic processes in marked populations, Springer, New York, pp 255–269.

Pollock KH (1982) A capture–recapture design robust to unequal probability of capture. Journal of Wildlife Management 46:752–757.

Ward GD (1978) Habitat use and home range of radio-tagged opossums *Trichosurus vulpecula* (Kerr) in New Zealand lowland forest. In: Montgomery GG (ed) The ecology of arboreal folivores. Smithsonian Institute Press, Washington DC, pp 267–287.

Table S1: Summary of data for case studies

a. Ovenbird

	Year				
	2005	2006	2007	2008	2009
Occasions	9	10	10	10	10
Detections	41	49	57	33	35
Animals	20	22	26	19	16

b. Brushtail possum

	Capture session					
	Feb'96	Jun'96	Sep'96	Feb'97	Jun'97	Sep'97
Occasions	5	5	5	5	5	5
Detections	450	494	328	383	372	375
Animals	223	206	148	162	154	135

Table S2: Estimated parameters of five movement models for ovenbird and brushtail possum data fitted using full and sparse kernels (radius 30 cells). Scale parameter α, shape parameter β (also used for added proportion of non-movers in zero-inflated models, suffix 'zi'). 95% CI in parentheses ('—' not calculated).

a. Ovenbird

	$\hat{\alpha}$				$\hat{\beta}$			
Kernel	Full		Sparse		Full		Sparse	
BVN	139	(91, 211)	136	(90, 205)				
BVE	91	(53,155)	88	(51,151)				
BVT	21.3	(3.1,147)	14.5	(0.3,830)	4e-07	(—)	3e-06	(—)
BVNzi	1e+05	(—)	4e+05	(—)	0.457	(0.249,0.682)	0.468	(0.248,0.701)
BVEzi	8e+08	(—)	3e+08	(—)	0.457	(0.249,0.682)	0.468	(0.248,0.701)

b. Brushtail possum

	$\hat{\alpha}$				$\hat{\beta}$			
Kernel	Full		Sparse		Full		Sparse	
BVN	20.5	(18.4, 22.9)	19.9	(17.8, 22.3)				
BVE	13.0	(11.8, 14.3)	12.7	(11.5, 14.0)				
BVT	1.08	(0.92, 1.27)	0.12	(0.10, 0.14)	5e-07	(—)	3e-06	(—)
BVNzi	119.3	(90.1, 158.0)	110.4	(84.9, 143.5)	0.884	(0.848, 0.912)	0.886	(0.849, 0.914)
BVEzi	73.6	(48.8, 110.9)	66.2	(45.0, 97.3)	0.870	(0.829, 0.902)	0.869	(0.827, 0.902)

Table S3: Estimated detection parameters of a static model and five movement models fitted to ovenbird and brushtail possum data using full and sparse kernels. Halfnormal hazard model, λ_0 baseline hazard, σ spatial scale. 95% CI in parentheses ('—' not calculated).

a. Ovenbird

	$\hat{\lambda}_0$				$\hat{\sigma}$ m			
Kernel	Full		Sparse		Full		Sparse	
Static	0.022 (0.017, 0.028)				98.9 (85.6, 114.2)			
BVN	0.031	(0.024, 0.040)	0.031	(0.024,0.040)	76.1	(66.0, 87.7)	76.4	(66.3, 88.0)
BVE	0.031	(0.024, 0.041)	0.031	(0.024, 0.041)	75.1	(65.3, 86.3)	75.4	(65.5, 86.7)
BVT	0.031	(0.024, 0.040)	0.031	(0.024,0.040)	74.8	(65.2, 85.9)	75.1	(65.4, 86.3)
BVNzi	0.030	(0.023, 0.039)	0.030	(0.023, 0.039)	75.6	(66.1, 86.6)	75.9	(66.2, 86.9)
BVEzi	0.030	(0.023, 0.039)	0.030	(0.023, 0.039)	75.6	(66.1, 86.6)	75.8	(66.2, 86.9)

b. Brushtail possum

	$\hat{\lambda}_0$				$\hat{\sigma}$ m			
Kernel	Full		Sparse		Full		Sparse	
Static	0.082 (0.077, 0.087)				36.1 (35.3, 37.0)			
BVN	0.104	(0.097, 0.111)	0.103	(0.096, 0.110)	31.7	(30.8, 32.7)	31.9	(31.0, 32.8)
BVE	0.115	(0.107, 0.122)	0.113	(0.106, 0.121)	30.1	(29.3, 30.9)	30.3	(29.5, 31.2)
BVT	0.116	(0.109, 0.124)	0.114	(0.107, 0.121)	29.9	(29.1, 30.7)	30.2	(29.4, 30.9)
BVNzi	0.114	(0.106, 0.121)	0.112	(0.105, 0.119)	30.2	(29.4, 31.0)	30.4	(29.7, 31.2)
BVEzi	0.115	(0.107, 0.122)	0.113	(0.106, 0.120)	30.1	(29.3, 30.9)	30.3	(29.5, 31.1)

Table S4: Estimated survival and recruitment from a static model and five movement models fitted to ovenbird and brushtail possum data using full and sparse kernels. ϕ survival, f *per capita* recruitment. 95% CI in parentheses ('—' not calculated).

a. Ovenbird

	$\hat{\phi}$				$\hat{f}$			
Kernel	Full		Sparse		Full		Sparse	
Static	0.529 (0.412, 0.643)				0.443 (0.317, 0.619)			
BVN	0.652	(0.474, 0.796)	0.647	(0.473, 0.789)	0.311	(0.167, 0.580)	0.318	(0.174, 0.578)
BVE	0.661	(0.475, 0.808)	0.655	(0.471, 0.802)	0.302	(0.156, 0.584)	0.308	(0.162, 0.585)
BVT	0.666	(0.484, 0.809)	0.660	(0.479, 0.804)	0.297	(0.156, 0.567)	0.304	(0.161, 0.572)
BVNzi	0.740	(0.516, 0.884)	0.735	(0.508, 0.882)	0.216	(0.081, 0.577)	0.221	(0.083, 0.588)
BVEzi	0.740	(0.516, 0.884)	0.735	(0.508, 0.882)	0.216	(0.081, 0.577)	0.221	(0.083, 0.588)

b. Brushtail possum

		$\hat{\phi}$				$\hat{f}$			
Kernel	Season	Full		Sparse		Full		Sparse	
Static	1	0.698 (0.608, 0.775)				0.152 (0.086, 0.269)			
	2	0.422 (0.331, 0.518)				0.026 (0.008, 0.082)			
	3	0.774 (0.654, 0.861)				0.170 (0.090, 0.321)			
BVN	1	0.698	(0.608, 0.775)	0.698	(0.608, 0.775)	0.141	(0.077, 0.258)	0.141	(0.077, 0.258)
	2	0.423	(0.332, 0.520)	0.423	(0.332, 0.520)	0.027	(0.009, 0.084)	0.027	(0.009, 0.084)
	3	0.774	(0.655, 0.861)	0.774	(0.655, 0.861)	0.155	(0.079, 0.305)	0.156	(0.080, 0.305)
BVE	1	0.699	(0.609, 0.776)	0.699	(0.609, 0.776)	0.139	(0.075, 0.257)	0.138	(0.075, 0.256)
	2	0.423	(0.332, 0.520)	0.423	(0.332, 0.521)	0.024	(0.007, 0.084)	0.024	(0.007, 0.085)
	3	0.775	(0.655, 0.862)	0.774	(0.655, 0.861)	0.154	(0.078, 0.304)	0.154	(0.078, 0.303)
BVT	1	0.712	(0.620, 0.789)	0.712	(0.620, 0.789)	0.130	(0.066, 0.254)	0.130	(0.066, 0.254)
	2	0.436	(0.342, 0.535)	0.435	(0.341, 0.534)	0.009	(0.001, 0.165)	0.009	(0.001, 0.170)
	3	0.788	(0.665, 0.874)	0.787	(0.664, 0.873)	0.151	(0.074, 0.308)	0.150	(0.074, 0.307)
BVNzi	1	0.712	(0.620, 0.790)	0.711	(0.619, 0.789)	0.127	(0.064, 0.253)	0.129	(0.066, 0.253)
	2	0.437	(0.343, 0.537)	0.435	(0.341, 0.534)	0.010	(0.001, 0.166)	0.012	(0.001, 0.131)
	3	0.788	(0.664, 0.874)	0.785	(0.663, 0.872)	0.150	(0.073, 0.308)	0.151	(0.074, 0.308)
BVEzi	1	0.712	(0.620, 0.789)	0.711	(0.619, 0.788)	0.128	(0.065, 0.253)	0.130	(0.066, 0.254)
	2	0.437	(0.342, 0.536)	0.435	(0.341, 0.534)	0.010	(0.001, 0.156)	0.012	(0.001, 0.130)
	3	0.787	(0.664, 0.874)	0.785	(0.663, 0.872)	0.150	(0.073, 0.308)	0.151	(0.074, 0.307)