

# Supplementary Information for

Global synthesis of conservation studies reveals the importance of small habitat patches for biodiversity

Brendan A. Wintle, Heini Kujala, Amy Whitehead, Alison Cameron, Sam Veloz, Aija Kukkala, Atte Moilanen, Ascelin Gordon, Pia E. Lentini, Natasha C.R. Cadenhead, Sarah A. Bekessy

Brendan A. Wintle

Email: [brendanw@unimelb.edu.au](mailto:brendanw@unimelb.edu.au)

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Supplementary text

Tables S1 to S2

Figure S1 and S2

References for SI citations

## Supplementary Information Text

**S1. Review of patch size, isolation and species richness.** A variety of approaches have been used to explore the relative importance of small fragments of habitat in fragmented landscapes, though empirical studies directly addressing the question are sparse, and results surprisingly mixed. Landscape ecology studies tend to reinforce the importance of large tracts of intact land for creating internal habitats that harbor species with particular requirements typically rare in the landscape (1). Similarly, classic results from metapopulation ecology highlight the role of patch size in mediating local extinction risk (2). But the evidence does not all point in one direction (3–5). Williams *et al.* (6) studied populations of rare and threatened plants in fragmented landscapes and found that “area and isolation had little effect on the probability of local extinction”. Fischer & Lindenmayer (7) studied the distribution of bird species in two fragmented landscapes in Australia; patchy natural forests embedded in a matrix of exotic pine plantations, and natural forest fragments in a matrix of cleared agricultural landscape. They found that over 90 species of birds in a local region were not confined to large patches, though there was no quantitative comparison of the relative conservation importance of small and large patches. Radford *et al.* (8) analysed bird species richness as a function of proportional vegetation cover in fragmented landscapes and found that richness declined rapidly when the proportion of regional tree cover dropped below 10%, though this study did not explicitly address the relative importance of patch size and location for bird species richness in those landscapes. The role of scattered trees and small isolated habitat patches in conserving biodiversity in fragmented landscapes is well articulated, though conclusions are drawn from relatively small-scale analyses of particular groups of species (18). Tulloch *et al.* (9) analysed the spatial distribution of major vegetation types in Australia and found that 22% were represented in small patches (<1000 ha) in over half of their extent, highlighting the importance of addressing how small patches are dealt with in the policy context, though they make no attempt to quantify the relative conservation value of small and large, or connected and isolated patches. Harrison (10) found that although endemic local ( $\alpha$ ) plant diversity was lower on isolated California serpentine patches than equal sized patches within large continuous serpentine outcrops, among site diversity ( $\beta$ ) was higher among the isolated patches than patches within the larger outcrops. Ogle *et al.* (11) provide evidence for the importance of small, isolated patches based on specific ecological circumstance in which sensitive species were less susceptible to damage from feral pigs in small patches. A further set of studies have been synthesized to better understand the traits that predispose individual species to be particularly sensitive to fragmentation (20, 22), though these provide no specific quantification of the relative importance of small versus large patches. Disagreement exists in the literature about the relative importance of habitat loss, fragmentation, and patch shape in driving biodiversity loss or persistence (4, 5).

## S2. Supplementary methods.

### *Input data and statistical modelling code*

All raw data inputs to this study and R code used in data handling and statistical analysis are available at the University of Melbourne figshare site:

<https://doi.org/10.26188/5bf75966a7e78>

The folder /data\_for\_web/ contains all Zonation prioritization maps for the case study locations listed in Table S2. Independent variables in each study location were generated from vegetation maps for each of those locations. The patch stats and buffer variables are available in the same location with prefixes ‘patchid’, ‘patchstats’ and ‘Buff’ respectively

with a number corresponding to the case study location. Case study codes are given in ‘study\_locations.csv’.

The same folder contains an R workspace ‘data\_for\_web’ and into that workspace, the full set of scripts can be loaded ‘small patches model - FINAL.R’. Steps in the data loading, manipulation, and modelling can be found in that script with comments indicating the purpose of each line of code.

**Table S1. Spatial conservation prioritization case studies used in our analysis.**

Case study	No. species	Taxonomic groups	Spatial grain (cell size)	Spatial Extent (km <sup>2</sup> )	Natural veg (% cover)	Original vegetation map grain	Veg ref	Case study ref
Madagascar	2 315	Amphibians, insects, mammals, plants, reptiles	930m	587 040	16%	30m	(14)	(15)
Northern Hunter Region	686	Amphibians, birds, mammals, plants, reptiles	100m	15 748	53%	100m	(16)	(17)
Southern Hunter Region	569	Amphibians, birds, mammals, plants, reptiles	100m	4 300	56%	100m	(16)	(18)
Melbourne	30	Amphibians, birds, fish, invertebrates, mammals, reptiles	80m	5 120	43%^	250m	(19)	(20)
Perth	189*	Birds, invertebrates, mammals, plants, reptiles	100m	8 500	68%	100m	(21)	(22)
Southwest Slopes, NSW	130	Birds, insects, mammals	100m	15 000	12%	25m	(23)	(24)

Pacific Northwest USA	26	Birds	1km	192 970	69%	30m	(25)	(26)
Austria	147	Amphibians, birds, mammals, reptiles	1.5km	83 879	60%	100m	(27)	(28)
Belgium	96	Amphibians, birds, mammals, reptiles	1.5km	30 528	27%	100m	(27)	(28)
Bulgaria	186	Amphibians, birds, mammals, reptiles	1.5km	110 994	51%	100m	(27)	(28)
Croatia	173	Amphibians, birds, mammals, reptiles	1.5km	56 594	61%	100m	(27)	(28)
Czech Republic	133	Amphibians, birds, mammals, reptiles	1.5km	78 866	45%	100m	(27)	(28)
Denmark	83	Amphibians, birds, mammals, reptiles	1.5km	42 931	21%	100m	(27)	(28)
Estonia	103	Amphibians, birds, mammals, reptiles	1.5km	45 227	66%	100m	(27)	(28)
Finland	100	Amphibians, birds, mammals, reptiles	1.5km	338 424	82%	100m	(27)	(28)
France	195	Amphibians, birds, mammals, reptiles	1.5km	640 679	36%	100m	(27)	(28)
Germany	146	Amphibians, birds,	1.5km	357 376	33%	100m	(27)	(28)

		mammals, reptiles						
Hungary	144	Amphibians, birds, mammals, reptiles	1.5km	93 030	27%	100m	(27)	(28)
Ireland	48	Amphibians, birds, mammals, reptiles	1.5km	70 273	33%	100m	(27)	(28)
Italy	206	Amphibians, birds, mammals, reptiles	1.5km	301 338	46%	100m	(27)	(28)
Latvia	111	Amphibians, birds, mammals, reptiles	1.5km	64 589	59%	100m	(27)	(28)
Lithuania	117	Amphibians, birds, mammals, reptiles	1.5km	65 300	41%	100m	(27)	(28)
Netherlands	96	Amphibians, birds, mammals, reptiles	1.5km	41 543	16%	100m	(27)	(28)
Poland	150	Amphibians, birds, mammals, reptiles	1.5km	312 679	36%	100m	(27)	(28)
Portugal	138	Amphibians, birds, mammals, reptiles	1.5km	92 212	55%	100m	(27)	(28)
Romania	184	Amphibians, birds, mammals, reptiles	1.5km	238 397	40%	100m	(27)	(28)
Slovakia	143	Amphibians, birds, mammals, reptiles	1.5km	49 035	52%	100m	(27)	(28)

Slovenia	147	Amphibians, birds, mammals, reptiles	1.5km	20 273	70%	100m	(27)	(28)
Spain	208	Amphibians, birds, mammals, reptiles	1.5km	505 990	51%	100m	(27)	(28)
Sweden	119	Amphibians, birds, mammals, reptiles	1.5km	447 435	80%	100m	(27)	(28)
United Kingdom	91	Amphibians, birds, mammals, reptiles	1.5km	242 495	33%	100m	(27)	(28)

\*This study also utilised 39 threatened ecological vegetation communities as an attribute in their analysis.

^This value includes waterways suitable for aquatic species.

Studies were chosen so that no arbitrary patch size or isolation settings were used to calculate priorities. In one case (Melbourne) the published study used a ‘boundary quality penalty’ multiplier that biased priorities toward larger, intact and less isolated patches of habitat. This analysis was re-run to compute priorities without that penalty applied. All *Zonation* prioritization maps are available via the *figshare* link provided above.

**Table S2. Patch metrics used in statistical analyses.** Each of the metrics described in this table were mapped for the case study regions based on vegetation mapping in the region. These metrics were used as surrogates of vegetation patch size, fragmentation and isolation. Apart from *Vegetation in 5km radius*, all variables were based on those defined in the *FRAGSTATS* package (v4) (29).

<b>Variable name (units, range)</b>	<b>Description</b>	<b>Reference</b>
Vegetation in 5km radius  (percentage) [0,100]	Percentage of raster cells within 5 km of the focal cell that contain habitat/vegetation. A single hectare patch of habitat greater than 5 km from the nearest other patch would receive a value of 0 in the buffer variable. A single hectare cell in the middle of a contiguous 10,000 ha square patch would receive a value of 100, if the 5-km radius buffer were used. A cell closer to the edge of the same patch would receive a lower score, depending on how close to the edge it was and whether other patches were close by. Extremely low values of the buffer variable (0–20) indicate the cell is embedded in a small and isolated patch. Intermediate values of the buffer variable (20–80) indicated moderate patch size with moderate isolation distance, or membership of a large but perhaps elongate patch. High values of the buffer variable (80–100) indicate membership of a large, contiguous area of habitat, or a small patch embedded in a highly connected landscape, close to other patches.	#
Patch perimeter  (m)	The perimeter (m) of the vegetation patch of which the focal cell is a member.	*
Patch area  (km <sup>2</sup> )	The size of the vegetation patch of which the focal cell is a member.	*
Perimeter-to-area ratio  (m/m <sup>2</sup> ) [0, inf)	The ratio of the perimeter (m) of the patch to the area (m <sup>2</sup> ) of that patch. It is a simple metric of shape complexity (one that changes with patch size).	*
Core area  (m <sup>2</sup> ) [0, inf)	The size of the vegetation patch, including only those cells that are surrounded by other cells of that patch (i.e., excluding edge cells). Thus, core area refers the interior area of patches after a user-specified (here, 1 cell deep) edge buffer is eliminated. The edge buffer represents the distance at which the “core” or interior of a patch is unaffected by the edge of the patch. Core area = 0 when every location within the patch is ≤1 cell from the edge.	*
Core area index	A relative index that quantifies core area as a percentage of patch area (i.e., the percentage of the patch that is comprised of core area). The index = 0 when the	*

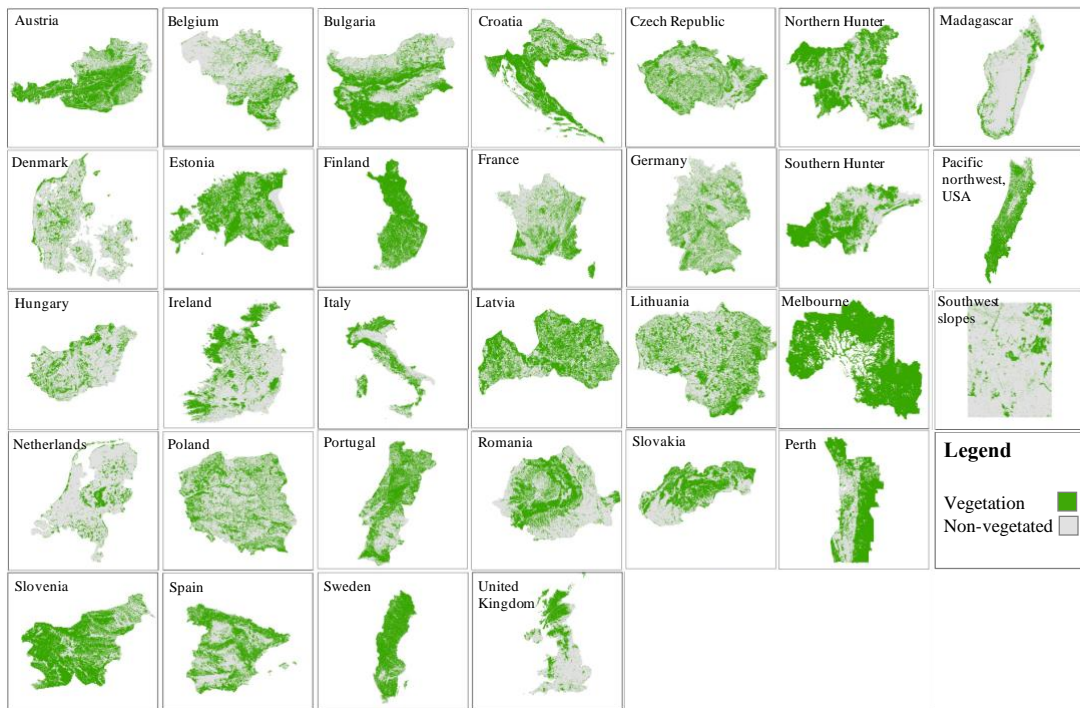
(%) [0–100]	patch contains no core area, and it approaches 100 when the patch – because of size, shape, and edge width – contains mostly core area.	
Number of core cells (n)	The number of cells in the core area; that is, those cells that have no length along the edge of the patch and are only adjacent to other patch-cells (see above for more details on the definition of “core area”).	^
Fractal dimension index (m/m <sup>2</sup> ) (1,2)	An index of patch shape, fractal dimension reflects shape complexity across a range of spatial scales (patch sizes). A fractal dimension greater than 1 indicates a departure from simple, Euclidean geometry (i.e., an increase in shape complexity). The index approaches 1 for shapes with very simple perimeters such as squares and approaches 2 for shapes with highly convoluted perimeters. <i>Preferred over perimeter-area ratio because it is not scale dependent.</i>	*
Shape index (index) [1, inf)	The patch perimeter (m) divided by the square root of patch area (m <sup>2</sup> ), adjusted by a constant to account for a square standard. This metric of shape complexity gives an idea of the irregularity of the shape of the patch. When the index = 1 the patch is a square, and the index increases as patch shape becomes more irregular. Unlike the perimeter-to-area ratio, this index does not change with the size of the patch.	*^

\* <http://www.umass.edu/landeco/research/fragstats/documents/fragstats.help.4.2.pdf>

^ <https://cran.r-project.org/web/packages/SDMTools/SDMTools.pdf>

# <https://scrogster.wordpress.com/2012/10/05/applying-a-circular-moving-window-filter-to-raster-data-in-r/>





**Figure S1. Vegetation maps of each case study area.** Green area shows the vegetated cells used in each analysis. Maps are not shown to scale, in order to maximise visibility of layers.

***Additional statistical modelling method details and raw model outputs***

R code for statistical modelling is available at the Figshare weblink provided above. However, some raw model outputs are provided here to simplify access.

The full model fitted after backward selection using the *StepAIC* function is summarized here:

Call:

```
glm(formula = z.logit ~ poly(stan.area, 3) + poly(stan.veg, 3) +
  poly(stan.fracdim, 3) + poly(stan.perimarearatio, 3) + poly(stan.autocov,
  3) + stan.area:stan.fracdim, data = unweight.stan1)
```

Deviance Residuals:

Min	1Q	Median	3Q	Max
-12.0498	-1.0394	-0.0226	1.0301	12.1292

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	0.03163	0.00829	3.815	0.000136 ***
poly(stan.area, 3)1	-253.29553	7.51914	-33.687	< 2e-16 ***
poly(stan.area, 3)2	-19.99770	2.86870	-6.971	3.16e-12 ***
poly(stan.area, 3)3	73.49809	2.54922	28.832	< 2e-16 ***
poly(stan.veg, 3)1	-109.20304	2.53679	-43.048	< 2e-16 ***
poly(stan.veg, 3)2	90.13663	1.93989	46.465	< 2e-16 ***
poly(stan.veg, 3)3	-49.02146	1.88312	-26.032	< 2e-16 ***

poly(stan.fracdim, 3)1	111.61647	6.40813	17.418	< 2e-16	***
poly(stan.fracdim, 3)2	-25.78365	2.42753	-10.621	< 2e-16	***
poly(stan.fracdim, 3)3	49.67937	2.37153	20.948	< 2e-16	***
poly(stan.perimarearatio, 3)1	-67.64333	2.40906	-28.079	< 2e-16	***
poly(stan.perimarearatio, 3)2	60.75760	2.29966	26.420	< 2e-16	***
poly(stan.perimarearatio, 3)3	-48.60501	2.66155	-18.262	< 2e-16	***
poly(stan.autocov, 3)1	38.90481	2.16295	17.987	< 2e-16	***
poly(stan.autocov, 3)2	-34.70217	1.78787	-19.410	< 2e-16	***
poly(stan.autocov, 3)3	73.51192	1.76647	41.615	< 2e-16	***
stan.area:stan.fracdim	0.83513	0.02829	29.519	< 2e-16	***

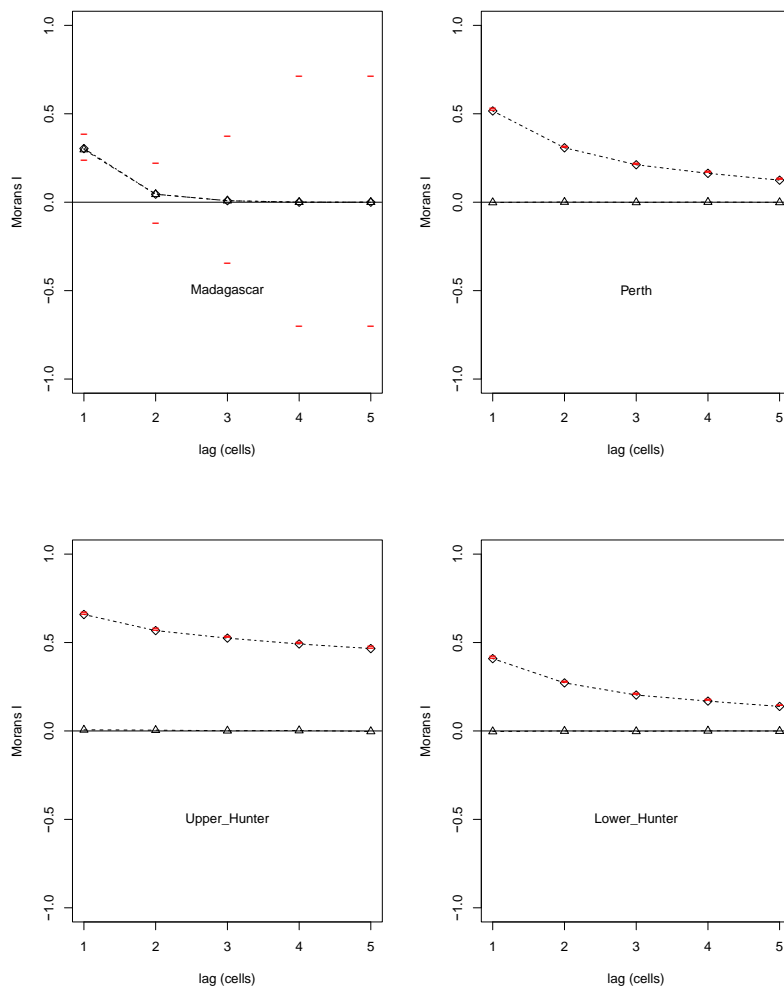
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Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

### ***Computing the auto-covariate for inclusion in regression modelling***

The presence of residual autocorrelation indicates a breach of the independence assumption of linear models (30). The use of an autocovariate is often proposed as a means of alleviating residual spatial autocorrelation in linear models and GLMs (31). An autocovariate value was computed for each cell in the landscape as a weighted sum of the dependent variable (conservation value) in the cells surrounding the focal cell. This calculation was conducted using the *spdep* library in R (32). This calculation was undertaken for each case study separately as it was assumed that the neighborhood of influence relevant to the calculation of autocovariate values did not extent across case study borders, though this may not have always held in the European case studies.

Plots of raw and residual autocorrelation (correlograms) for each study location are provided in the file 'auto\_plots.pdf' in the online material at the Figshare website. These indicate quite clearly that residual spatial autocorrelation, measured using Moran's I calculated on model residuals for each case study except for Madagascar, was either zero or minimal across the short lag distances over which autocorrelation is normally strongest. Residual autocorrelation in the Madagascan case study remained significant, if relatively weak ( $I \sim 0.4$ ), at the shortest lag distance only. A sample of four are provided here (Fig. S2) for indication, including the Madagascar plot which was the only case study in which inclusion of the autocovariate in GLMs was unsuccessful in bringing residual autocorrelation to zero.



**Figure S2.** Correlograms of model residuals for four of the 31 case studies. Triangles show model residual autocorrelation with the inclusion of the autocovariate and diamonds show residual autocorrelation without the inclusion of the autocovariate in the final model. Residual correlation is reduced to zero with the inclusion of the autocovariate in all but the Madagascar case study model, though residual autocorrelation is only weakly positive at the first lag distance in that model. The remainder of the case study correlograms can be viewed via the Figshare link provided above.

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