Supplementary Information for: Habitat fragmentation reduces survival and drives source–sink dynamics for a large carnivore

Journal: Ecological Applications

Authors: Anna C. Nisi, John F. Benson, Richard King, Christopher C. Wilmers

Appendix S1

Section S1: Puma time-to-event data

The Cox Proportional Hazards model assumes that the instantaneous risk of mortality (hazard ($h_i(t)$)) for each individual i at time t is related to both the baseline hazard at time t ($h_0(t)$), which all animals experience, as well as covariate effects experienced by that individual. This relationship takes the form:

$$h_i(t) = h_0(t)e^{\boldsymbol{x_i\beta}}$$

in which $\boldsymbol{x_i}$ is a vector of covariates associated with individual i at time t, $\boldsymbol{\beta}$ is a vector of coefficients that describe the effects of each covariate $\boldsymbol{x}$ on mortality risk. Because all individuals monitored at the same time experience the same baseline hazard, the hazards ratio between any two individuals under observation is constant over time. For a series of event times for mortalities from m monitored animals (t_1 through t_m), this property allows for covariate effects ($\boldsymbol{\beta}$) to be estimated through the following partial likelihood function (Cox 1972, Hosmer et al. 1999):

$$PL(\boldsymbol{\beta}) = \prod_{i=1}^{m} \frac{e^{\boldsymbol{x_i\beta}}}{\sum_{j\in R_i} e^{\boldsymbol{x_j\beta}}}$$

This partial likelihood function compares the instantaneous hazard experienced by each individual mortality event (i in 1 through m) with the hazard experienced by animals under observation at time t_i (or in the risk set, R_i) in a matched-case framework.

Here, we were interested in how exposure to housing density impacts mortality risk. As such, for each time of death t_i, we calculated housing density experienced 45 days prior to t_i for all animals in the risk set at t_i and coded start and stop times accordingly. For each death, animals in the risk set "entered" at $t_i - 1$ and "exited" at $t_i + 1$, while the animal that died "entered" at $t_i - 1$ and "exited" at t_i. Because the partial likelihood function only incorporates information from times of death, this approach allowed us to directly compare the exposure of animals in the risk set at each t_i to the animal that died without losing any information (Fieberg and DelGuidice 2009). The alternative approach would have been to regularly update exposure at regular intervals (e.g., each month), but this would result in individuals dying early- or mid-month having a different time scale of exposure than animals in the risk set.

Section S2: Semivariance analysis

We used semivariance analysis to inform our choice of 45 day periods as long-term movement. For resident (non-dispersing) pumas that had >60 days of data, we used the *ctmm* package to fit semivariograms for each individual (Calabrese et al. 2016). Next, to characterize asymptotic behavior we fit Michaelis-Menten functions to semivariograms, which take the form $\frac{ax}{b+x}$, in which a represents the asymptotic semivariance (in km^2) and b is the half-saturation parameter, or half the time it takes to reach the asymptote. The long-term asymptote for semivariograms denotes long-term home-ranging behavior (Fleming et al. 2014, Calabrese et al. 2016), so the parameter b sheds light on how long it takes for an animal to traverse its home range. We calculated mean half-saturation values for resident animals, and considered mean home-range-crossing time to be twice the value of the mean half saturation value.

In our population, the mean half-saturation value was 7.80 days for females, 10.26 days for males, and 8.90 days overall. The long-term 45-day intervals thus represent >2 home range crossings for males and > 2.9 home range crossings for females.

Section S3: Resource selection function covariate descriptions

We included covariates that had been identified as important drivers of habitat selection in previous analyses (Wilmers et al. 2013, Nisi et al. 2022), including housing density and its quadratic term, percent vegetative cover, distance to nearest perennial steam (National Hydrography Dataset, USGS[1]), topographic slope, topographic position index (TPI), the interaction between slope and TPI. All covariates were rasterized at 30m resolution and were standardized (centered by mean and scaled by standard deviation). We used generalized estimating equations (GEE) to account for temporal autocorrelation and estimate robust standard error, treating each puma as a separate cluster (Prima et al. 2017).

We calculated housing density across the study area by applying radially-symmetric Epanechnikov kernels with a 150m kernel radius to each building location from digitized satellite maps, and then summing the kernel densities within each grid cell (Wilmers et al. 2013). This method and kernel radius was found to be the scale at which pumas responded to housing during movement in a prior analysis of puma habitat selection in this area (Wilmers et al. 2013). Housing density data were right skewed, with pumas spending the majority of their time at low levels of housing density. To account for this we cube root transformed housing density so that standardized coefficients were more easily interpretable over the range of housing density that pumas used (Nisi et al. 2022).

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[1] https://www.usgs.gov/core-science-systems/ngp/national-hydrography

Vegetation categories from 30m-resolution California GAP data (Gap Analysis Project, USGS[2]) were assigned cover classes (0 or 1), and we used a focal analysis with a 90m moving window to calculate percent cover. The following vegetative categories were coded as cover: Forest and woodland systems (CN Level 1); Developed (CN Level 2, within Human Use Land); Chaparral, Deciduous dominated savanna and glade, and Conifer dominated savanna (CN Level 2, within Shrubland, steppe and savanna systems); all Floodplain and riparian (CN Level 2, within Riparian and wetland systems) except for Inter-Mountain Basins Greasewood Flat and North American Warm Desert Wash (CN Level 3); and Harvested Forest - Northwestern Conifer Regeneration (CN Level 3), Recently burned forest (CN Level 3), Introduced Upland Vegetation - Treed (CN Level 3), Introduced Riparian and Wetland Vegetation (CN Level 3).

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[2] https://www.usgs.gov/core-science-systems/science-analytics-and-synthesis/gap

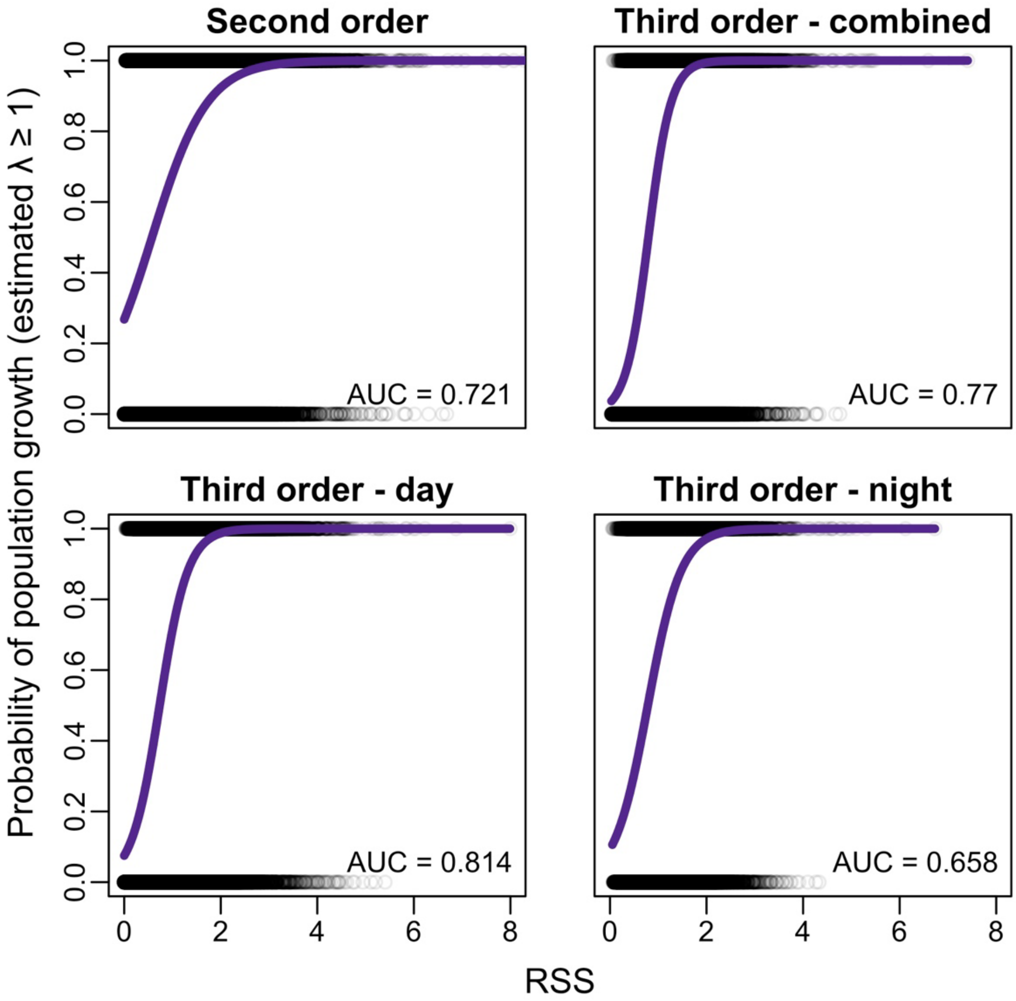

Figure S1. Relationship between predicted population status (1 = growth [*λ* ≥ 1] or 0 = decline [*λ* < 1]) and relative selection strength (RSS).

Table S1. Coefficient estimates for models of second- and third-order puma habitat selection. Combined models are models that include both daytime and nighttime puma locations, while the “day” and “night” models only include locations during those respective times. “HD” denotes housing density, and “TPI” denotes topographic position index. Coefficient estimates are presented with standard errors in parentheses, and * denote *p*-values <0.001.

	Second order	Third order		
Covariate	Combined	Combined	Day	Night
HD	-0.123* (0.004)	-0.136* (0.004)	-0.301* (0.007)	-0.020* (0.005)
HD^2	-0.114* (0.002)	-0.051* (0.003)	-0.117* (0.006)	-0.050* (0.003)
Slope	-0.115* (0.003)	-0.125* (0.003)	-0.083* (0.004)	-0.158* (0.003)
TPI	0.190* (0.002)	0.170* (0.002)	0.179* (0.003)	0.162* (0.003)
Cover	0.351* (0.003)	0.102* (0.003)	0.193* (0.004)	0.047* (0.003)
River	-0.219* (0.002)	0.023* (0.002)	0.044* (0.004)	0.010* (0.003)
Slope*TPI	-0.090* (0.003)	-0.091* (0.002)	-0.093* (0.003)	-0.088* (0.003)
N used	204809	204809	84893	119256

Supplementary References

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