A peer-reviewed version of this preprint was published in PeerJ on 4 April 2018.

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Density and population viability of coastal marten: a rare and geographically isolated small carnivore

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Pacific martens (Martes caurina) in coastal forests of Oregon and northern California in the United States are rare and geographically isolated, prompting a petition for listing under the Endangered Species Act. If listed, regulations have the potential to substantially influence land-use decisions and forestry on public and private lands, but no estimates of population size, density, and viability of remnant marten populations are available for evaluating their conservation status. We used GPS telemetry, territory mapping, and spatial mark-recapture to estimate population size and density within the current extent of Pacific martens in central Oregon, within coastal forest in the Oregon dunes national recreational area. We then estimated population viability at differing levels of human-caused mortality (e.g. roadkill). We estimated 63 adult martens (95% Credible Interval: 58-73) and 73 (range: 46-91) potential territories across two subpopulations separated by a large barrier (Umpqua River). Marten density was 1.02 per km², the highest reported in North America. Using population viability analysis, extinction risk for a subpopulation of 30 martens ranged from 34% to 100% with two or more annual human-caused mortalities. Absent broad-scale restoration of forest to conditions which support marten populations, limiting human-caused mortalities would likely have the greatest conservation impact.
Density and population viability of coastal marten: a rare and geographically isolated small carnivore

RH: Trajectories of a small isolated marten population

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Abstract

Pacific martens (Martes caurina) in coastal forests of Oregon and northern California in the United States are rare and geographically isolated, prompting a petition for listing under the Endangered Species Act. If listed, regulations have the potential to substantially influence land-use decisions and forestry on public and private lands, but no estimates of population size, density, and viability of remnant marten populations are available for evaluating their conservation status. We used GPS telemetry, territory mapping, and spatial mark-recapture to estimate population size and density within the current extent of Pacific martens in central Oregon, within coastal forest in the Oregon dunes national recreational area. We then estimated
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Keywords: density, marten, *Martes americana, Martes caurina*, population viability analysis, spatial mark-recapture
Introduction

Conserving wildlife while maintaining economic growth is one of the most pervasive conservation and policy challenges globally. This balance in the United States is enforced in part by the Endangered Species Act (ESA), which can restrict land use on both public and private lands for the benefit of imperiled species. Forests of the Pacific Northwest of North America highlight challenges between land use and endangered species conservation as demonstrated by the history with Northern Spotted Owl (*Strix occidentalis caurina*, Simberloff 1987). Timber production dominates land use in western Oregon, and annual harvests there exceeded 8 to 9 billion board-feet prior to ESA listing of the Northern Spotted Owl in 1990. Production subsequently declined to roughly 4 billion board-feet after logging on public lands was curtailed following the owl’s listing, but the Oregon coast range still annually supports a $7.1 billion industry and provides nearly 60,000 jobs (Simmons et al. 2016). Now decades after the conflict over listing the Northern Spotted Owl, a distinct population segment of a forest-dependent small carnivore is a litigation target due to listing petitions by the ESA (2017).

Pacific martens (*Martes caurina*) are a small carnivore, considered a habitat specialist closely associated with structurally complex forests to the extent that they are considered a “management indicator species” by federal land management agencies for intact late-seral montane forests with seasonal snow cover in the western United States (Buskirk & Ruggiero 1994; Zielinski 2013). Humboldt martens (*Martes caurina humboldtensis*), a subspecies of Pacific marten, occupy near-coast forests with limited or no snow cover, and have significantly declined both in numbers and geographic range prompting petitions to list the subspecies as threatened or endangered (Center for Biological Diversity 2010; Moriarty et al. 2016a; Slauson et al. 2007; Zielinski et al. 2001). Recent extensive distributional surveys revealed that Humboldt
Marten are restricted to three isolated populations in coastal Oregon and northern California (Moriarty et al. 2016a; Zielinski et al. 2001). The furthest north of these populations is isolated by >50km from the nearest adjacent population (Moriarty et al. 2016a), and appears to occupy a <500-m wide band of young (<70 years old) coastal forest growing on sand dunes along the margin of the Pacific Ocean in central Oregon. When considering population status, the U.S. Fish and Wildlife Service concluded martens were most common on federal lands, that martens were a late-seral specialist, and overall threats to population persistence were low; the petition was withdrawn in 2015 (U.S. Fish and Wildlife Service 2015). The withdrawal speculated martens were likely most abundant in the central coast of Oregon because of a relatively high number of road-killed individuals in the past three decades ($n=14$, Zielinski et al. 2001, p. 487), and extensive late-seral reserves on federal lands that provided habitat (Slauson 2015); however, no surveys were conducted.

Accurate estimates of population size provide the basis for determining long-term viability and conservation of species under stochastic environmental, genetic, or demographic perturbations (O'Grady et al. 2004). Assessing the causes of scarcity provides the basis for population viability under future conditions (Caughley 1994). This may be of particular interest for small, isolated populations where human-caused mortality is a threat and available habitat is limited (Ferreras et al. 2001). Estimates of population size and density can provide foundational data used to articulate future conservation and management objectives (Ciucci et al. 2015; Frankham 1995). Projecting population trajectories under different scenarios with data collected using multiple field and analytical methods can increase confidence in current and future population estimates (Lindenmayer & Possingham 1996; Sollmann et al. 2013). Despite attempts
to list Humboldt marten populations, an estimate of population status in coastal Oregon has
never been calculated.

We used multiple field (i.e., radio-telemetry, mark-recapture) and analytical methods
(i.e., spatial mark-recapture, territory mapping) to evaluate the population size of two
subpopulations that together comprise the marten population in Oregon’s central coast region.
We then used a population viability analysis to determine the effect size of human-caused
mortality (i.e., legal trapping, vehicle strikes) on these isolated marten subpopulations. Finally,
we compared density and territory sizes of martens in coastal Oregon to other North American
populations (M. caurina, M. americana) to infer whether resource availability was relatively

Methods

Study area

We surveyed the northernmost population of Humboldt martens along the central Oregon
cost (hereafter, “Oregon Dunes”). The Oregon Dunes consisted of a narrow north-south strip of
costal forest along the margin of the Pacific Ocean bounded by two large rivers to the north and
south (Siuslaw and Coos Rivers), US Highway 101 to the east, and separated into northern and
southern subpopulations by the Umpqua River (600-m wide, Fig. 1). The study area was
comprised of nearly equal parts open sand and forest growing on nutrient poor sandy soils
(Christy et al. 1998). Much of the forested area was the result of recent expansion over the last
70 years coincident with stabilization of near-coast beaches by European beach grass (Amophila
arenaria) into mounded fore dunes, which limited sand deposition and facilitated vegetation
expansion into previously shifting open sand (Christy et al. 1998). The northern and southern
portions had 36.9 km² and 25.6 km² of forested area, respectively (Fig. 1). Minimum and
maximum temperatures in July and January were 10.1°C and 20.3°C and 3.2°C and 10.2°C, respectively. Annual precipitation averaged 176 cm, and occurred primarily between November and March (Western Regional Climate Center 1971-2016). Elevation within the study area ranged from eight to 80 m.

Coastal forest was dominated by young (<50 years-old) shore-pine (Pinus contorta contorta) and Sitka spruce (Picea sitchensis). The sub-tree canopy was dense, extended to 4 m in height and was dominated by willow (Salix hookeri), Pacific waxmyrtle (Myrica californica), salal (Gaultheria shallon), and slough sedge (Carex obnupta) on seasonally flooded sites, and berry-producing ericaceous shrubs (e.g., evergreen huckleberry (Vaccinium ovatum), salal) on seasonally dry sites (Christy et al. 1998). Coastal forest differed substantially from inland forest east of highway 101 in vegetation age, structure, and composition (Eriksson 2016). Inland forests were a mix of young Douglas-fir (Pseudotsuga menziesii) plantations (0–80 years) and late-seral forest (>80 years old) reserved primarily as habitat for northern spotted owl (Strix occidentalis) and marbled murrelet (Brachyramphus marmoratus, Davis et al. 2015). Martens were legally harvested throughout Oregon with 0 to 4 martens trapped per year from central coastal Oregon (Verts & Carraway 1998).

**Territory estimates**

We live-trapped and radio-marked Pacific martens from October to December 2015 using traps spaced approximately 1 km apart using methods described in Moriarty et al. (2017) and Mortenson & Moriarty (2015). We fit adult martens (i.e. animals estimated to be greater than two years old) with a VHF (Advanced Telemetry Systems, Minnesota, USA; 29 g in weight) or GPS/VHF collar (Quantum 4000 Micro-Mini GPS collars, Telemetry Solutions, California, USA; 41-44 g; or G10 snap technology GPS, Advanced Telemetry Systems, Minnesota, USA;
Each collar antenna was marked with a unique pattern of reflective tape, which we used to identify individuals using remote cameras (Fig. 2). All capture and handling procedures were approved by the USDA Forest Service’s Institute for Animal Care and Use Committee (USFS 2015-002) under an Oregon Department of Fish and Wildlife Scientific Take Permit (ODFW 119-15). We removed collars in late January and February 2016.

We programmed GPS collars to collect locations separated by 5 minutes, and only included locations in our analyses with predicted errors < 30 m and time periods where data were collected for > 72 consecutive hours (details in Moriarty et al. 2017). We located individuals with VHF-only collars at least twice per week. We only used VHF locations where the variance of x and y was < 400 m determined with Location of a Signal Ecological Software Solutions LLC. We estimated individual marten space-use, which we refer to as the territory because these areas were traversed within one week, exclusively used, and apparently defended against conspecifics of the same sex (Moriarty et al. 2017). We used the t-LoCoH package in R to estimate 99% LoCoH territories (i.e., discarding 1% of the furthest dispersed points; Lyons et al. 2013). Local convex hulls were constructed using 35 neighboring locations ($k = 35$), regardless of time between locations ($s = 0$; Lyons et al. 2013; R Core Team 2013). These parameterizations best reflected marten spatial behavior in our study (e.g. exclusive territories), limited the formation of multiple activity centers, and provided a smoothed outer contour boundary.

**Spatial mark-recapture**

We deployed 31 remote camera stations in December 2015 and early January 2016 along a linear transect (henceforth, “SMR transect”) that overlapped the area occupied by a subset of radio-tracked martens within forest cover (Fig. 3). We defined forest cover as vegetation > 1 m
in height and estimated it using a light detection and ranging (LiDAR) canopy height model.

Camera stations were distributed $311 \pm 91$ m (mean $\pm$ 1 standard deviation) apart with a minimum goal of four camera stations accessible to each female (Sun et al. 2014). Each station consisted of attractants (~250g chicken, ~100 g strawberry jam; olfactory lure), and a remotely triggered camera (Fig. 2).

We estimated the density of martens from our photographic data using spatial mark-recapture models. Briefly, spatial mark-recapture models identify the number of unique individuals that live in a given study area by estimating individual-specific capture probabilities as a function of the location of their latent activity centers (Royle et al. 2014). A population size is then calculated by determining how many activity centers of individuals, captured or unaptured, are present within the study area.

We created a discrete state-space $S$ defined as a 100-m grid within a 5-km buffer around camera stations, excluding cells in the Pacific Ocean. We defined camera sighting data as the Poisson distributed random variable $y_{ij}$ representing the number of days marten $i$ was sighted at camera station $j$ as:

$$y_{ij} \sim \text{Pois}(\lambda_{ij}K)$$

where $\lambda_{ij}$ is a function describing the average daily rate of detecting marten $i$ at camera station $j$ and $K$ was equal to the number of sampling days ($n = 39$). We hypothesized that the average daily rate varied by sex and the distance between the station and their latent activity center ($\lambda_{ij} = p_i \times e^{-d_{ij}^2 / 2\sigma^2_k}$). We incorporated a sex-specific covariate on detection to determine whether males and females had different rates of detection, and modeled the average daily rate of detecting individual $i$ as a function of an intercept and a sex-effect ($\logit(p_i) = \beta_0 + \beta_1 \times \text{sex}_i$). We used the half-normal decay function, where $d_{ij}$ was the distance between the camera station
where an individual was located and the location of its latent activity center \((s_i)\), and \(\sigma_k\) is the standard deviation of a bivariate normal distribution reflecting space-use, calculated independently for each sex \(k\).

We modeled activity center locations using a non-homogeneous Poisson point process in \(S\) to examine whether locations of marten activity centers in the Oregon Dunes were associated with forest cover. We calculated the mean forest cover in each grid cell \(g\) in \(S\), and used an intensity function to model the location of activity centers as:

\[
\mu_g = \text{area}_g \times e^{a_0 + a_1 \times \text{forest cover}_g + a_2 \times \text{forest cover}_g^2}
\]

where the predicted number of activity centers in grid cell \(g\) \((\mu_g)\) is a function of an intercept \((\alpha_0)\) and the linear \((\alpha_1)\) and quadratic effects of forest cover \((\alpha_2)\). Finally, we incorporated telemetry data and the number of unmarked individuals that visited our camera stations to improve model fit and precision (Royle et al. 2013; Sollmann et al. 2013). Martens can travel to any point in their territory within one-hour (Moriarty et al. 2016b; Moriarty et al. 2017). Accordingly, we only used locations that were at least one-hour apart to ensure independence of telemetry locations (Sollmann et al. 2013).

We fit our models using data augmentation (Royle & Dorazio 2008; Royle & Young 2008) and the Markov-Chain Monte Carlo (MCMC) methods of JAGS (Plummer 2003) with the jagsUI package (Kellner 2014) in R v. 3.2.3 (R Core Team 2016). We used uninformative prior distributions for all parameters (see Appendix 1 for full JAGS code). We calculated estimates from 4,500 MCMC samples, taken from three chains run for 5,000 iterations, thinned by three, following a burn-in of 500. We assessed model convergence by examining trace plots and \(\hat{R}\) values for parameter estimates (Gelman & Hill 2007; Gelman et al. 2013). All \(\hat{R}\) values were < 1.1, indicating chain convergence. We used a habitat mask of > 40% forest cover, which was the
minimum amount of forest cover used by martens in our study, to estimate the density of martens in the SMR transect.

We compared territory sizes between our two subpopulations using a general linear model with two parameters: sex and location in our study area. Lacking any significant differences, we assumed density could be extrapolated to estimate subpopulation sizes (Moriarty et al. 2017).

**Determining carrying capacity using territory mapping**

We estimated the potential number of marten territories in the Oregon Dunes using territory length, which appeared appropriate given that coastal forest and observed marten territories were distributed in a long, narrow north-south strip (Fig. 3). We estimated territory length as two times the distance from the center of each territory to its outermost edge. We then generated 10 iterations of random territory centers within forest cover, with a minimum distance between territory centers equal to the estimated mean and lower and upper 95% confidence intervals of territory length from observed territories. We discarded hypothetical territories that did not contain an amount of forest cover greater than the observed minimum forest cover in marten territories.

**Population viability**

We assessed the risk of extirpation for a marten subpopulation over the next 40 years in the context of threats from human activities (e.g., trapping, roadkill; Gerber et al. 2004). We estimated the maximum intrinsic population growth rate using a modified Euler-Lotka equation proposed by Skalski et al. (2008)

\[ e^{ra} - e^{-M(r)^a - ml_a} = 0, \]
where $r$ is the maximum intrinsic growth rate, $a$ is the age at first birth, $m$ is the fecundity constant (number of female offspring/female/year), $e^{-M}$ is the probability of survival, and $l_a$ is the probability of survival to maturity. We obtained a range of parameter estimates associated with the maximum reproductive output of two closely related species of North American martens ($\textit{Martes americana, Martes caurina}$) in wild populations from the literature (Table 1). Estimates of $r$ are sensitive to uncertainty in annual survival, $e^{-M}$; we estimated maximum intrinsic growth rate ($r$) assuming average, high, and very high survival rates (0.7, 0.8, 0.9 respectively, McCann et al. 2010) to obtain three values of $r = 0.143, 0.205, 0.268$ (Table 2). We used the intermediate value of $r = 0.205$ in our population projections, but we also implemented a stochastic element with $\sigma = 0.06$ such that the low and high estimates of $r$ would bracket one standard deviation from the mean.

We simulated the dynamics of a population beginning at carrying capacity using initial values of the population size ($K$) equal to 20, 30, and 40 to illustrate how estimates of extirpation risk depend on our uncertainty about the current population size (see population estimates in Results). The density-dependent population dynamics are given by the discrete theta-logistic model with an annual mortality component:

$$N_{t+1} = e^{r(1 - \left(\frac{N}{K}\right)^{\theta})} + \epsilon - H_t,$$

where $\epsilon \sim N(0, \sigma)$, with $\sigma = 0.06$ based on the variation in our best estimate of $r$ (Table 2), and mortalities resulting from trapping and road-kills as $H_t \sim \text{Pois}(\lambda)$. The rate parameter of the Poisson distribution, $\lambda$, defines both the mean and variance of the annual mortality through road-kills or trapping ($H_t$), which takes values of $\lambda = 1, 2, 3$ martens in our models (36 martens harvested 1969–1995, 0–4/year; Verts & Carraway 1998). We assumed a small density-independent harvest to illustrate how extirpation risk can be influenced by relatively low
mortality rates. We conservatively assumed a standard logistic population growth ($\theta = 1$) but also assumed that density-dependent declines in per-capita growth occurred at higher population densities ($\theta = 2$), which is expected for long-lived mammals (Boyce 1992). We simulated population trajectories with three initial conditions ($K = 20, 30, \text{and } 40$), three stochastic human-caused mortality rates ($\lambda = 1, 2, \text{and } 3$), and two values of the strength of density dependence using theta ($\theta = 1, 2$). Finally, we report observed mortalities during our study period. Where appropriate, we report results as mean $\pm 1$ standard deviation.

Results

We captured and radio-collared six female (three VHF, three GPS/VHF) and four male martens (all GPS/VHF). Our GPS collars collected $1139 \pm 1149$ locations over $15.7 \pm 14.4$ days on 8 individuals (4 males, 4 females), and we collected $35 \pm 2$ locations over $75 \pm 29$ days for three females with VHF-only collars. We estimated territory sizes to be $0.7 \pm 0.1 \text{ km}^2$ for females and $1.8 \pm 0.6 \text{ km}^2$ for males, and territories were composed primarily of $>40\%$ forest cover: females $= 0.5 \pm 0.1 \text{ km}^2$ and males $= 0.8 \pm 0.3 \text{ km}^2$. Mean forest cover at radio-telemetry locations was $75\%$ ($25\text{-}75\%$ quantile range $= 60\text{-}96\%$, $n = 11$ martens; Appendix 2, Figure 1).

Territory sizes did not differ significantly between the northern and southern portions of the study area ($t = 0.5, p = 0.68$). Territory length was $1.9 \pm 0.3 \text{ km}$ for females and $2.8 \pm 0.3 \text{ km}$ for males. Territory sizes were smaller and density was higher in coastal Oregon compared to other North American populations (Fig. 4). Across populations, territory size was negatively correlated with density (Fig. 4).

Density and population size

We incorporated $77.3 \pm 59.2$ telemetry locations per individual into our SMR models. No marked individuals of the same sex were observed visiting the same camera station, and $1.1 \pm$
0.5 km and 3.4 ± 1.8 km was the furthest distance between camera station detections for females and males, respectively (Figs. 3b,3c).

We estimated marten density as 1.02 ± 0.09 individuals/km² (95% Credible Interval (Crl) = 0.92–1.16), or 8.78 ± 0.75 individuals within the SMR area. Assuming density was constant across the 62.5 km² forested study area, we estimated median population size as 63: 37 (Crl = 34–43) north of the Umpqua River and 26 (Crl = 24–30) south. These results were comparable to our findings using territory mapping (mean = 40 [range = 26–50] and 34 [range = 20–41]; Table 3). Both techniques yielded similar estimates of population size, but the credible intervals using SMR were more precise (Table 3). We estimated the sex-ratio of our population using SMR to be 3.7 ± 1.3 females to one male (Table 4). Male martens had a lower detection probability (median [95% CrI] on the normal scale = 0.24 [0.19, 0.3]) than females (0.42 [0.24, 0.75]; Table 4). Neither the linear nor the quadratic effects of forest cover affected the distribution of activity centers, although there was a non-significant trend for martens to select areas with higher forest cover (Table 4).

Population viability

We estimated that two or more annual human-caused mortalities on martens (e.g. trapping and road-kills) would lead to a substantial risk of extirpation, particularly at smaller population sizes (Figs. 5, 6) and for θ = 1 (Fig. 5) relative to θ = 2 (Fig. 6). The likelihood of extirpation when θ = 1 for a population of 30 individuals, which approximated the average of our estimates for each subpopulation, was 32% and 99% with two and three annual mortalities, respectively. The probabilities decreased to 1% and 60% when θ = 2 with two and three annual mortalities, respectively. The probability of extirpation increased to 89-100% and 65-100% for a population of 20 individuals with two or three annual mortalities. We observed four mortalities,
two in each subpopulation, from August 2015 to April 2016: two road-killed females on small
(i.e., two-way) paved roads, one male on highway 101, and one female to predation attributed to
predation by a great-horned owl (*Bubo virginianus*).

**Discussion**

Using only anecdotal evidence, the central coast Oregon population was estimated to be
relatively abundant, aiding the withdrawal from consideration for listing under the ESA. Using
two field and analytical methods and scientifically collected data, we estimated population size
of Humboldt martens inhabiting coastal forests in the Oregon dunes to be <75 individuals.

Primarily due to small population size, long-term viability of the two subpopulations we
monitored appears to be highly sensitive to even a few annual human-caused mortalities (i.e.
legal trapping, road-kills). Although ecological conditions in coastal forests appear to be
favorable for martens, a lack of alternative habitat nearby, consistent human-caused mortality,
and isolation may cause these populations to become extirpated in the future.

Unsurprisingly, we demonstrated that consistent human-caused stochastic mortality
reduced population viability. Human-caused mortality, however, is rarely stochastic. The timing,
location, and sex-ratio of mortalities may provide additional resolution as to whether mortalities
are likely to contribute to a population decline (Haight et al. 1998). Because martens are long-
lived with both delayed breeding and implantation (Mead 1994), eliminating breeding female
martens with established territories, similar to nesting birds in plowed fields, may have a
disproportionate effect on viability than recruitment by juveniles (Grüebler et al. 2008).

Alternatively, juvenile recruitment was identified as the most important population-level
parameter in other marten populations, but limited resources were likely to constrain juvenile
recruitment and population growth (Manlick et al. 2017). Enhancing connectivity to other marten
populations would provide a mechanism for juvenile recruitment and potentially mitigate concerns about genetic isolation of the central coast Oregon population but connectivity is likely severely limited for coastal populations in Oregon because of distance and barriers to movement (large rivers, human settlement) separating populations. Given that juvenile recruitment is unlikely to increase due to resource limits and population isolation, ensuring that other population parameters remain stable, such as adult survival, may be the most beneficial opportunity to maintain or increase population size.

Density of martens in the Oregon Dunes was nearly twice as high as estimates from other populations (Flynn & Schumacher 2009; Sirén et al. 2016). Similar to other carnivores, territory size is likely to be correlated with foraging resources (Kittle et al. 2015; Mattisson et al. 2016). We therefore predict that the smaller territories and higher densities we documented here were due to greater year-round foraging opportunities (e.g., over-wintering passerine birds; Eriksson 2016; Nagorsen et al. 1989), and a favorable foraging environment. Specifically, we predict that dense vegetation mediates interactions with competitors and predators, and provides spaces to hunt and avoid predators similar to snow in winter (Andruskiw et al. 2008). Accordingly, the lack of martens inland, continued road kills along Highway 101, and evidence of previous breeding by adult females in our study provide circumstantial evidence that the Oregon Dunes functions as a refuge for martens. Moreover, coastal forests may have the potential to function as climactic refugium at low latitudes for martens (Channell & Lomolino 2000), particularly if winter snow pack limits habitat for marten populations in high-elevation montane forests (Halofsky et al. 2017; Spencer et al. 2015; Suffice et al. 2017).

The apparent absence of martens in inland late-seral forest and reserves indicate that these areas are not sufficient to conserve marten populations (Moriarty et al. 2016b). Whether
inland forest restoration can or should be applied to mimic the ecological conditions found in
diverse young forest of the Oregon dunes demonstrates the complicated trade-offs in endangered
species management, particularly because such restoration is most likely to occur on public lands
in direct competition for resources used by Northern Spotted Owls. Ultimately, short-term
management for coastal martens (i.e., next 40-years) appears relatively straightforward: maintain
or increase habitat extent and limit human-caused mortalities.

Conclusions

Endangered species management inevitably comes with tradeoffs. In central coast
Oregon, resource requirements for two similar sized predators with large spatial area
requirements appear mutually exclusive, and current inland reserves appear inadequate for
martens. Our snap-shot assessment of population size of Humboldt martens in central Oregon,
and future projections using best available estimates for population growth, identified even a
small amount of sustained human-caused mortalities may increase likelihood of population
extirpation. Although population growth rate may be most sensitive to changes in juvenile
recruitment, the near-complete isolation, limited resources, and lack of connectivity to other
populations may mean that juvenile recruitment cannot be influenced through management.
Influencing adult survival, through limits on human-caused mortalities may provide short-term
benefits for this population. Endangered species management requires reliable estimates of
population status and viability but long-term monitoring of population processes is needed to
evaluate predictions of population viability and whether populations are declining (Caughley
1994).

Acknowledgements
We received considerable aid with field logistics, vehicles, housing, and equipment from the Central Coast Ranger District, Siuslaw National Forest. Adam Kotaich did much of the field; also thanks to Cindy Burns, Crystal Mullins, and Deanna Williams for quickly using field data for management-related discussions; and to the team that has incorporated martens into the updated Oregon Dunes Restoration Strategy.

**Funding statement:** Survey efforts were funded by the USDA Forest Service Pacific Northwest Research Station, Siuslaw National Forest, and U.S. Fish and Wildlife Service’s Portland Office.

**References**


http://www.nature.com/nature/journal/v403/n6765/suppinfo/403084a0_S1.html


10.1186/s13002-017-0180-9


Table Captions

Table 1. Input values for coastal marten viability analysis.

Table 2. Three estimates of maximum intrinsic growth rate (r) bracketing our uncertainty from most to least conservative life history assumptions of annual survival for population viability modeling.

Table 3. Estimates of marten population size using spatial mark-recapture (SMR) and territory mapping. Both estimates were extrapolated from areas where we estimated density (northern study area; density = 1.02 km²; SMR), or radio-tracked martens (territory mapping). Male and female ratios for SMR assumed a ratio of 3.59 females per one male (estimated mean, Table 2). Intervals are Credible intervals (SMR) and 95% confidence intervals (territory mapping).

Table 4. Summary statistics from a spatial mark-recapture model with telemetry data that estimated the density of Pacific martens (Martes caurina) in our study area in the Oregon Dunes Recreation Area from Oct. 2015 to Jan. 2016.

Figure captions

Figure 1. We collected location data on Pacific marten (Martes caurina) in the coastal Oregon Dunes Recreation Area, west of highway 101, Oct 2015 to Jan 2016. The study area was bounded to the north and south by the Siuslaw and Coos Rivers, respectively, and divided by the Umpqua River in the center, which is approximately 600 m wide where it meets the Pacific Ocean. This area has extensive fragmentation with vegetated islands surrounded by open sand. Photograph credit: Katie Moriarty. Imagery sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
Figure 2. Examples of uniquely marked individual martens. From top left: a) female marten with GPS collar sniffing strawberry jam, b) male marten with unique GPS collar with two antennas, c) female with three reflective bands, and d) male marten with two reflective bands (middle, end of antenna). Each station included an olfactory lure (Gusto, Minnesota Trapline Products, Pennacock, MN) and baits that were checked and replaced weekly. We set remote cameras (Bushnell Aggressor, model: 119776; Bushnell Corporation, Overland Park, KS) two to three m from bait and programmed them to record a photo every second after motion was detected. We reviewed photographic clusters where the same individual was present in consecutive photos, and identified individual martens for the mark-recapture analysis. We discarded photographic clusters if we were unable to distinguish whether a marten was marked or unmarked (<1% of all photos collected). Photograph credit: remote cameras set by Mark Linnell.

Figure 3. We conducted a spatial mark-recapture study using remotely triggered cameras and Pacific marten (Martes caurina) with unique reflective markings on their collars in the northern portion of the coastal Oregon Dunes Recreation Area from 4 December 2015 to 12 January 2016. Here, we show a) location of all camera stations, b) stations which detected female martens, c) stations which detected male martens, and unmarked martens (large black dots), and d) an example of randomly generated female territory centers (squares) and coincident territorial outlines (dashed lines) used in territory mapping. For b and c, individual martens are depicted by unique colored dots (camera station detections), and outlines (outer boundary of territories). Imagery sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
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Other studies were conducted in Maine, USA which included estimates from three study areas (Payer and Harrison 1999), central British Columbia, Canada (Poole et al. 2004), New Hampshire, USA (Siren et al. 2016), and Quebec, Canada (Godbout and Ouellet 2010).

Figure 5. One-thousand density-dependent stochastic population projections (gray) for a subpopulation of Pacific marten (Martes caurina humboldtensis) from the theta-logistic model, assuming a linear relationship between per-capita population growth and population size (θ = 1) beginning at three values of carrying capacity (K; 20, 30, or 40), and three human-caused mortalities averaging 1, 2, or three marten annually. The mean population trajectory is given by the black line, and the red line signifies the pseudo-extinction threshold of 2 individuals. The proportion of trajectories falling below this threshold is the probability of extirpation Pr(ext). Stochastic mortalities averaging two or more marten lead to substantial extirpation risk within the next 40 years, particularly for smaller values of K.

Figure 6. One-thousand density-dependent stochastic population projections (gray) for a subpopulation of Pacific marten (Martes caurina humboldtensis) from the theta-logistic model assuming a convex relationship between per-capita population growth and population size (θ = 2
beginning at three values of carrying capacity ($K; 20, 30, \text{ or } 40$), and three human-caused mortalities averaging 1, 2, or three marten annually. A $\theta > 1$ may be more realistic for long-lived mammals, because the onset of density dependence likely occurs at higher population densities once crowding of territories occurs; assuming values where $\theta > 1$ is less conservative because the population will be more permissive to mortality or other mortality. The mean population trajectory is given by the black line, and the red line signifies the pseudo-extinction threshold of two individuals. The proportion of trajectories falling below this threshold is the probability of extirpation $Pr(\text{ext})$. Within the next 40 years, stochastic mortalities averaging two or more marten lead to substantial extirpation risk, particularly for smaller values of $K$. 
Table 1. Input values for coastal marten viability analysis.
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<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at first parturition</td>
<td>2</td>
<td>Mead (1994)</td>
</tr>
<tr>
<td>Average number of kits/year ($m$)</td>
<td>1.5</td>
<td>Anne and Schladweiler (1997), Flynn and Schumaker (2016)</td>
</tr>
<tr>
<td>Survivorship to first parturition ($l_a$)</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Kit survival (age 0-1)</td>
<td>0.49</td>
<td>Johnson et al. (2009)</td>
</tr>
<tr>
<td>Yearling survival (age 1-2)</td>
<td>0.7</td>
<td>Average for North American martens, McCann et al. 2010</td>
</tr>
<tr>
<td>Range of adult survival (age 2+)</td>
<td>0.7-0.9</td>
<td>McCann et al. 2010</td>
</tr>
</tbody>
</table>

Anne and Schladweiler (1997) reported mean pregnancy rates of 85.5% and litter size of 2.6 for martens in Montana, leading to an estimate of $m = 1.1$, and Flynn and Schumaker (2016) observed pregnancy rates of martens in Southeast Alaska averaging only 47% over seven years while litter size was 3.3, producing an estimate of $m = 0.78$. 
Bracketing uncertainty with three maximum intrinsic growth rates (r).

Table 2. Three estimates of maximum intrinsic growth rate (r) bracketing our uncertainty from most to least conservative life history assumptions of annual survival for population viability modeling.
Table 2. Three estimates of maximum intrinsic growth rate ($r$) bracketing our uncertainty from most to least conservative life history assumptions of annual survival for population viability modeling.

<table>
<thead>
<tr>
<th>Annual Survival ($e^{-M}$)</th>
<th>Female kits per year ($m$)</th>
<th>Age of first parturition ($a$)</th>
<th>Survivorship to age at first parturition ($l_a$)</th>
<th>Maximum intrinsic growth rate ($r$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>1.5</td>
<td>2</td>
<td>0.35</td>
<td>0.143</td>
</tr>
<tr>
<td>0.8</td>
<td>1.5</td>
<td>2</td>
<td>0.35</td>
<td>0.205</td>
</tr>
<tr>
<td>0.9</td>
<td>1.5</td>
<td>2</td>
<td>0.35</td>
<td>0.268</td>
</tr>
</tbody>
</table>
Table 3 (on next page)

Estimates of marten population size using spatial mark-recapture (SMR) and territory mapping.

Table 3. Estimates of marten population size using spatial mark-recapture (SMR) and territory mapping. Both estimates were extrapolated from areas where we estimated density (northern study area; density = 1.02 km$^2$; SMR), or radio-tracked martens (territory mapping). Male and female ratios for SMR assumed a ratio of 3.59 females per one male (estimated mean, Table 2). Intervals are Credible intervals (SMR) and 95% confidence intervals (territory mapping).
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<table>
<thead>
<tr>
<th>Technique</th>
<th>Northern subpopulation</th>
<th>Southern subpopulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Interval</td>
</tr>
<tr>
<td>Spatial mark-recapture</td>
<td>37.2</td>
<td>33.9–42.4</td>
</tr>
<tr>
<td>Females</td>
<td>26.8</td>
<td>24.5–30.6</td>
</tr>
<tr>
<td>Males</td>
<td>10.4</td>
<td>9.4–11.8</td>
</tr>
<tr>
<td>Territory mapping</td>
<td>40</td>
<td>25.6–50.4</td>
</tr>
<tr>
<td>Females</td>
<td>24</td>
<td>16.6–33.8</td>
</tr>
<tr>
<td>Males</td>
<td>16</td>
<td>9–16.6</td>
</tr>
</tbody>
</table>
Summary statistics from a spatial mark-recapture model with telemetry data that estimated the density of Pacific martens.

Table 4. Summary statistics from a spatial mark-recapture model with telemetry data that estimated the density of Pacific martens (*Martes caurina*) in our study area in the Oregon Dunes Recreation Area from Oct. 2015 to Jan. 2016.
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (SD)</th>
<th>2.5</th>
<th>50</th>
<th>97.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (per km$^2$)</td>
<td>1.02 (0.09)</td>
<td>0.92</td>
<td>1.04</td>
<td>1.16</td>
</tr>
<tr>
<td>Abundance (# martens)</td>
<td>8.8 (0.76)</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma_{\text{male}}$ (km)</td>
<td>1.14 (0.05)</td>
<td>1.06</td>
<td>1.14</td>
<td>1.24</td>
</tr>
<tr>
<td>$\sigma_{\text{female}}$ (km)</td>
<td>0.28 (0.01)</td>
<td>0.27</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>Sex ratio (females:males)</td>
<td>3.59 (1.23)</td>
<td>2</td>
<td>3.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$\beta_0$ (intercept detection probability)</td>
<td>-1.6 (0.14)</td>
<td>-1.86</td>
<td>-1.6</td>
<td>-1.33</td>
</tr>
<tr>
<td>$\beta_1$ (sex effect on detection probability)</td>
<td>0.76 (0.19)</td>
<td>0.38</td>
<td>0.76</td>
<td>1.14</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>-6.76 (1.68)</td>
<td>-9.7</td>
<td>-6.77</td>
<td>-3.59</td>
</tr>
<tr>
<td>$\alpha_1$ (canopy)</td>
<td>6.52 (4.56)</td>
<td>-2.14</td>
<td>6.27</td>
<td>15.83</td>
</tr>
<tr>
<td>$\alpha_2$ (canopy$^2$)</td>
<td>-0.08 (4.14)</td>
<td>-8.67</td>
<td>0.06</td>
<td>8.02</td>
</tr>
</tbody>
</table>
Study area

Figure 1. We collected location data on Pacific marten (*Martes caurina*) in the coastal Oregon Dunes Recreation Area, west of highway 101, Oct 2015 to Jan 2016. The study area was bounded to the north and south by the Siuslaw and Coos Rivers, respectively, and divided by the Umpqua River in the center, which is approximately 600 m wide where it meets the Pacific Ocean. This area has extensive fragmentation with vegetated islands surrounded by open sand. Photo credit: Katie Moriarty. Imagery sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
- Camera and trap locations-north
- Camera and trap locations-south
- Coast highway 101

Oregon, USA

Pacific Ocean

Umpqua River

Kilometers
Figure 2

Photographs of uniquely marked martens

Figure 2. Examples of uniquely marked individual martens. From top left: a) female marten with GPS collar sniffing strawberry jam, b) male marten with unique GPS collar with two antennas, c) female with three reflective bands, and d) male marten with two reflective bands (middle, end of antenna). Each station included an olfactory lure (Gusto, Minnesota Trapline Products, Pennacock, MN) and baits that were checked and replaced weekly. We set remote cameras (Bushnell Aggressor, model: 119776; Bushnell Corporation, Overland Park, KS) two to three m from bait and programmed them to record a photo every second after motion was detected. We reviewed photographic clusters where the same individual was present in consecutive photos, and identified individual martens for the mark-recapture analysis. We discarded photographic clusters if we were unable to distinguish whether a marten was marked or unmarked (<1% of all photos collected). Photograph credit: remote cameras set by Mark Linnell.
Figure 3

Remote camera locations and territory mapping example for marten population estimates.

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Figure 4

North American marten densities and population sizes

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Figure 5

Marten population viability analysis, theta = 1

Figure 5. One-thousand density-dependent stochastic population projections (gray) for a subpopulation of Pacific marten (*Martes caurina humboldtensis*) from the theta-logistic model, assuming a linear relationship between per-capita population growth and population size (theta=1) beginning at three values of carrying capacity (K; 20, 30, or 40), and three human-caused mortalities averaging 1, 2, or three marten annually. The mean population trajectory is given by the black line, and the red line signifies the pseudo-extinction threshold of 2 individuals. The proportion of trajectories falling below this threshold is the probability of extirpation Pr(ext). Stochastic mortalities averaging two or more marten lead to substantial extirpation risk within the next 40 years, particularly for smaller values of K.
Figure 6

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