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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 km<sup>2</sup>, 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.

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

3 RH: Trajectories of a small isolated marten population

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14

15 **Abstract**

16 Pacific martens (*Martes caurina*) in coastal forests of Oregon and northern California in the

17 United States are rare and geographically isolated, prompting a petition for listing under the

18 Endangered Species Act. If listed, regulations have the potential to substantially influence land-

19 use decisions and forestry on public and private lands, but no estimates of population size,

20 density, and viability of remnant marten populations are available for evaluating their

21 conservation status. We used GPS telemetry, territory mapping, and spatial mark-recapture to

22 estimate population size and density within the current extent of Pacific martens in central

23 Oregon, within coastal forest in the Oregon dunes national recreational area. We then estimated

24 population viability at differing levels of human-caused mortality (e.g. roadkill). We estimated  
25 63 adult martens (95% Credible Interval: 58-73) and 73 (range: 46-91) potential territories across  
26 two subpopulations separated by a large barrier (Umpqua River). Marten density was 1.02 per  
27 km<sup>2</sup>, the highest reported in North America. Using population viability analysis, extinction risk  
28 for a subpopulation of 30 martens ranged from 34% to 100% with two or more annual human-  
29 caused mortalities. Absent broad-scale restoration of forest to conditions which support marten  
30 populations, limiting human-caused mortalities would likely have the greatest conservation  
31 impact.

32 Keywords: density, marten, *Martes americana*, *Martes caurina*, population viability analysis,  
33 spatial mark-recapture

34

## 35 Introduction

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

49 Pacific martens (*Martes caurina*) are a small carnivore, considered a habitat specialist  
50 closely associated with structurally complex forests to the extent that they are considered a  
51 “management indicator species” by federal land management agencies for intact late-seral  
52 montane forests with seasonal snow cover in the western United States (Buskirk & Ruggiero  
53 1994; Zielinski 2013). Humboldt martens (*Martes caurina humboldtensis*), a subspecies of  
54 Pacific marten, occupy near-coast forests with limited or no snow cover, and have significantly  
55 declined both in numbers and geographic range prompting petitions to list the subspecies as  
56 threatened or endangered (Center for Biological Diversity 2010; Moriarty et al. 2016a; Slauson  
57 et al. 2007; Zielinski et al. 2001). Recent extensive distributional surveys revealed that Humboldt

58 martens are restricted to three isolated populations in coastal Oregon and northern California  
59 (Moriarty et al. 2016a; Zielinski et al. 2001). The furthest north of these populations is isolated  
60 by >50km from the nearest adjacent population (Moriarty et al. 2016a), and appears to occupy a  
61 <500-m wide band of young (<70 years old) coastal forest growing on sand dunes along the  
62 margin of the Pacific Ocean in central Oregon. When considering population status, the U.S.  
63 Fish and Wildlife Service concluded martens were most common on federal lands, that martens  
64 were a late-seral specialist, and overall threats to population persistence were low; the petition  
65 was withdrawn in 2015 (U.S. Fish and Wildlife Service 2015). The withdrawal speculated  
66 martens were likely most abundant in the central coast of Oregon because of a relatively high  
67 number of road-killed individuals in the past three decades ( $n=14$ , Zielinski et al. 2001, p. 487),  
68 and extensive late-seral reserves on federal lands that provided habitat (Slauson 2015); however,  
69 no surveys were conducted.

70         Accurate estimates of population size provide the basis for determining long-term  
71 viability and conservation of species under stochastic environmental, genetic, or demographic  
72 perturbations (O'Grady et al. 2004). Assessing the causes of scarcity provides the basis for  
73 population viability under future conditions (Caughley 1994). This may be of particular interest  
74 for small, isolated populations where human-caused mortality is a threat and available habitat is  
75 limited (Ferrerias et al. 2001). Estimates of population size and density can provide foundational  
76 data used to articulate future conservation and management objectives (Ciucci et al. 2015;  
77 Frankham 1995). Projecting population trajectories under different scenarios with data collected  
78 using multiple field and analytical methods can increase confidence in current and future  
79 population estimates (Lindenmayer & Possingham 1996; Sollmann et al. 2013). Despite attempts

80 to list Humboldt marten populations, an estimate of population status in coastal Oregon has  
81 never been calculated.

82 We used multiple field (i.e., radio-telemetry, mark-recapture) and analytical methods  
83 (i.e., spatial mark-recapture, territory mapping) to evaluate the population size of two  
84 subpopulations that together comprise the marten population in Oregon's central coast region.  
85 We then used a population viability analysis to determine the effect size of human-caused  
86 mortality (i.e., legal trapping, vehicle strikes) on these isolated marten subpopulations. Finally,  
87 we compared density and territory sizes of martens in coastal Oregon to other North American  
88 populations (*M. caurina*, *M. americana*) to infer whether resource availability was relatively  
89 high for martens in coastal Oregon (Herr et al. 2009; Thompson & Colgan 1994).

## 90 **Methods**

### 91 **Study area**

92 We surveyed the northernmost population of Humboldt martens along the central Oregon  
93 coast (hereafter, "Oregon Dunes"). The Oregon Dunes consisted of a narrow north-south strip of  
94 coastal forest along the margin of the Pacific Ocean bounded by two large rivers to the north and  
95 south (Siuslaw and Coos Rivers), US Highway 101 to the east, and separated into northern and  
96 southern subpopulations by the Umpqua River (600-m wide, Fig. 1). The study area was  
97 comprised of nearly equal parts open sand and forest growing on nutrient poor sandy soils  
98 (Christy et al. 1998). Much of the forested area was the result of recent expansion over the last  
99 70 years coincident with stabilization of near-coast beaches by European beach grass (*Amophila*  
100 *arenaria*) into mounded fore dunes, which limited sand deposition and facilitated vegetation  
101 expansion into previously shifting open sand (Christy et al. 1998). The northern and southern  
102 portions had 36.9 km<sup>2</sup> and 25.6 km<sup>2</sup> of forested area, respectively (Fig. 1). Minimum and

103 maximum temperatures in July and January were 10.1°C and 20.3°C and 3.2°C and 10.2°C,  
104 respectively. Annual precipitation averaged 176 cm, and occurred primarily between November  
105 and March (Western Regional Climate Center 1971-2016). Elevation within the study area  
106 ranged from eight to 80 m.

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

### 119 **Territory estimates**

120 We live-trapped and radio-marked Pacific martens from October to December 2015 using  
121 traps spaced approximately 1 km apart using methods described in Moriarty et al. (2017) and  
122 Mortenson & Moriarty (2015). We fit adult martens (i.e. animals estimated to be greater than two  
123 years old) with a VHF (Advanced Telemetry Systems, Minnesota, USA; 29 g in weight) or  
124 GPS/VHF collar (Quantum 4000 Micro-Mini GPS collars, Telemetry Solutions, California,  
125 USA; 41-44 g; or G10 snap technology GPS, Advanced Telemetry Systems, Minnesota, USA;



126 27 g). Each collar antenna was marked with a unique pattern of reflective tape, which we used to  
127 identify individuals using remote cameras (Fig. 2). All capture and handling procedures were  
128 approved by the USDA Forest Service's Institute for Animal Care and Use Committee (USFS  
129 2015-002) under an Oregon Department of Fish and Wildlife Scientific Take Permit (ODFW  
130 119-15). We removed collars in late January and February 2016.

131 We programmed GPS collars to collect locations separated by 5 minutes, and only  
132 included locations in our analyses with predicted errors  $< 30$  m and time periods where data were  
133 collected for  $> 72$  consecutive hours (details in Moriarty et al. 2017). We located individuals  
134 with VHF-only collars at least twice per week. We only used VHF locations where the variance  
135 of  $x$  and  $y$  was  $< 400$  m determined with Location of a Signal Ecological Software Solutions  
136 LLC. We estimated individual marten space-use, which we refer to as the territory because these  
137 areas were traversed within one week, exclusively used, and apparently defended against  
138 conspecifics of the same sex (Moriarty et al. 2017). We used the t-LoCoH package in R to  
139 estimate 99% LoCoH territories (i.e., discarding 1% of the furthest dispersed points; Lyons et al.  
140 2013). Local convex hulls were constructed using 35 neighboring locations ( $k = 35$ ), regardless  
141 of time between locations ( $s = 0$ ; Lyons et al. 2013; R Core Team 2013). These  
142 parameterizations best reflected marten spatial behavior in our study (e.g. exclusive territories),  
143 limited the formation of multiple activity centers, and provided a smoothed outer contour  
144 boundary.

#### 145 **Spatial mark-recapture**

146 We deployed 31 remote camera stations in December 2015 and early January 2016 along  
147 a linear transect (henceforth, "SMR transect") that overlapped the area occupied by a subset of  
148 radio-tracked martens within forest cover (Fig. 3). We defined forest cover as vegetation  $> 1$  m

149 in height and estimated it using a light detection and ranging (LiDAR) canopy height model.  
150 Camera stations were distributed  $311 \pm 91$  m (mean  $\pm$  1 standard deviation) apart with a  
151 minimum goal of four camera stations accessible to each female (Sun et al. 2014). Each station  
152 consisted of attractants ( $\sim 250$ g chicken,  $\sim 100$  g strawberry jam; olfactory lure), and a remotely  
153 triggered camera (Fig. 2).

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

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

$$164 \quad y_{ij} \sim \text{Pois}(\lambda_{ij}K)$$

165 where  $\lambda_{ij}$  is a function describing the average daily rate of detecting marten  $i$  at camera station  $j$   
166 and  $K$  was equal to the number of sampling days ( $n = 39$ ). We hypothesized that the average  
167 daily rate varied by sex and the distance between the station and their latent activity center ( $\lambda_{ij} =$   
168  $p_i \times e^{(-d_{ij}^2 / 2\sigma_k^2)}$ ). We incorporated a sex-specific covariate on detection to determine whether  
169 males and females had different rates of detection, and modeled the average daily rate of  
170 detecting individual  $i$  as a function of an intercept and a sex-effect ( $\text{logit}(p_i) = \beta_0 + \beta_1 \times \text{sex}_i$ ). We  
171 used the half-normal decay function, where  $d_{ij}$  was the distance between the camera station

172 where an individual was located and the location of its latent activity center ( $s_i$ ), and  $\sigma_k$  is the  
173 standard deviation of a bivariate normal distribution reflecting space-use, calculated  
174 independently for each sex  $k$ .

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

$$179 \quad \mu_g = \text{area}_g \times e^{a_0 + a_1 \times \text{forest cover}_g + a_2 \times \text{forest cover}_g^2}$$

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

187 We fit our models using data augmentation (Royle & Dorazio 2008; Royle & Young  
188 2008) and the Markov-Chain Monte Carlo (MCMC) methods of JAGS (Plummer 2003) with the  
189 jagsUI package (Kellner 2014) in R v. 3.2.3 (R Core Team 2016). We used uninformative prior  
190 distributions for all parameters (see Appendix 1 for full JAGS code). We calculated estimates  
191 from 4,500 MCMC samples, taken from three chains run for 5,000 iterations, thinned by three,  
192 following a burn-in of 500. We assessed model convergence by examining trace plots and  $\hat{R}$   
193 values for parameter estimates (Gelman & Hill 2007; Gelman *et al.* 2013). All  $\hat{R}$  values were <  
194 1.1, indicating chain convergence. We used a habitat mask of > 40% forest cover, which was the

195 minimum amount of forest cover used by martens in our study, to estimate the density of martens  
196 in the SMR transect.

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

### 201 **Determining carrying capacity using territory mapping**

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

### 211 **Population viability**

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

$$216 \quad e^{ra} - e^{-M}(e^r)^{a-1} - ml_a = 0,$$

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

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

$$233 \quad N_{t+1} = e^{r\left(1 - \left(\frac{N}{K}\right)^\theta\right) + \varepsilon} - H_t,$$

234 where  $\varepsilon \sim N(0, \sigma)$ , with  $\sigma = 0.06$  based on the variation in our best estimate of  $r$  (Table 2), and  
 235 mortalities resulting from trapping and road-kills as  $H_t \sim Pois(\lambda)$ . The rate parameter of the  
 236 Poisson distribution,  $\lambda$ , defines both the mean and variance of the annual mortality through road-  
 237 kills or trapping ( $H_t$ ), which takes values of  $\lambda = 1, 2, \text{ or } 3$  martens in our models (36 martens  
 238 harvested 1969–1995, 0–4/year; Verts & Carraway 1998). We assumed a small density-  
 239 independent harvest to illustrate how extirpation risk can be influenced by relatively low

240 mortality rates. We conservatively assumed a standard logistic population growth ( $\theta = 1$ ) but  
241 also assumed that density-dependent declines in per-capita growth occurred at higher population  
242 densities ( $\theta = 2$ ), which is expected for long-lived mammals (Boyce 1992). We simulated  
243 population trajectories with three initial conditions ( $K = 20, 30,$  and  $40$ ), three stochastic human-  
244 caused mortality rates ( $\lambda = 1, 2,$  and  $3$ ), and two values of the strength of density dependence  
245 using theta ( $\theta = 1, 2$ ). Finally, we report observed mortalities during our study period. Where  
246 appropriate, we report results as mean  $\pm$  1 standard deviation.

## 247 **Results**

248 We captured and radio-collared six female (three VHF, three GPS/VHF) and four male  
249 martens (all GPS/VHF). Our GPS collars collected  $1139 \pm 1149$  locations over  $15.7 \pm 14.4$  days  
250 on 8 individuals (4 males, 4 females), and we collected  $35 \pm 2$  locations over  $75 \pm 29$  days for  
251 three females with VHF-only collars. We estimated territory sizes to be  $0.7 \pm 0.1$  km<sup>2</sup> for  
252 females and  $1.8 \pm 0.6$  km<sup>2</sup> for males, and territories were composed primarily of >40% forest  
253 cover: females =  $0.5 \pm 0.1$  km<sup>2</sup> and males =  $0.8 \pm 0.3$  km<sup>2</sup>. Mean forest cover at radio-telemetry  
254 locations was 75% (25-75% quantile range = 60-96%,  $n = 11$  martens; Appendix 2, Figure 1).  
255 Territory sizes did not differ significantly between the northern and southern portions of the  
256 study area ( $t = 0.5, p = 0.68$ ). Territory length was  $1.9 \pm 0.3$  km for females and  $2.8 \pm 0.3$  km for  
257 males. Territory sizes were smaller and density was higher in coastal Oregon compared to other  
258 North American populations (Fig. 4). Across populations, territory size was negatively correlated  
259 with density (Fig. 4).

## 260 **Density and population size**

261 We incorporated  $77.3 \pm 59.2$  telemetry locations per individual into our SMR models. No  
262 marked individuals of the same sex were observed visiting the same camera station, and  $1.1 \pm$

263 0.5 km and  $3.4 \pm 1.8$  km was the furthest distance between camera station detections for females  
264 and males, respectively (Figs. 3b,3c).

265 We estimated marten density as  $1.02 \pm 0.09$  individuals/km<sup>2</sup> (95% Credible Interval (CrI)  
266 = 0.92–1.16), or  $8.78 \pm 0.75$  individuals within the SMR area. Assuming density was constant  
267 across the 62.5 km<sup>2</sup> forested study area, we estimated median population size as 63: 37 (CrI =  
268 34–43) north of the Umpqua River and 26 (CrI = 24–30) south. These results were comparable to  
269 our findings using territory mapping (mean = 40 [range = 26–50] and 34 [range = 20–41]; Table  
270 3). Both techniques yielded similar estimates of population size, but the credible intervals using  
271 SMR were more precise (Table 3). We estimated the sex-ratio of our population using SMR to  
272 be  $3.7 \pm 1.3$  females to one male (Table 4). Male martens had a lower detection probability  
273 (median [95% CrI] on the normal scale = 0.24 [0.19, 0.3]) than females (0.42 [0.24, 0.75]; Table  
274 4). Neither the linear nor the quadratic effects of forest cover affected the distribution of activity  
275 centers, although there was a non-significant trend for martens to select areas with higher forest  
276 cover (Table 4).

### 277 **Population viability**

278 We estimated that two or more annual human-caused mortalities on martens (e.g.  
279 trapping and road-kills) would lead to a substantial risk of extirpation, particularly at smaller  
280 population sizes (Figs. 5, 6) and for  $\theta = 1$  (Fig. 5) relative to  $\theta = 2$  (Fig. 6). The likelihood of  
281 extirpation when  $\theta = 1$  for a population of 30 individuals, which approximated the average of our  
282 estimates for each subpopulation, was 32% and 99% with two and three annual mortalities,  
283 respectively. The probabilities decreased to 1% and 60% when  $\theta = 2$  with two and three annual  
284 mortalities, respectively. The probability of extirpation increased to 89-100% and 65-100% for a  
285 population of 20 individuals with two or three annual mortalities. We observed four mortalities,

286 two in each subpopulation, from August 2015 to April 2016: two road-killed females on small  
287 (i.e., two-way) paved roads, one male on highway 101, and one female to predation attributed to  
288 predation by a great-horned owl (*Bubo virginianus*).

## 289 **Discussion**

290 Using only anecdotal evidence, the central coast Oregon population was estimated to be  
291 relatively abundant, aiding the withdrawal from consideration for listing under the ESA. Using  
292 two field and analytical methods and scientifically collected data, we estimated population size  
293 of Humboldt martens inhabiting coastal forests in the Oregon dunes to be <75 individuals.  
294 Primarily due to small population size, long-term viability of the two subpopulations we  
295 monitored appears to be highly sensitive to even a few annual human-caused mortalities (i.e.  
296 legal trapping, road-kills). Although ecological conditions in coastal forests appear to be  
297 favorable for martens, a lack of alternative habitat nearby, consistent human-caused mortality,  
298 and isolation may cause these populations to become extirpated in the future.

299 Unsurprisingly, we demonstrated that consistent human-caused stochastic mortality  
300 reduced population viability. Human-caused mortality, however, is rarely stochastic. The timing,  
301 location, and sex-ratio of mortalities may provide additional resolution as to whether mortalities  
302 are likely to contribute to a population decline (Haight et al. 1998). Because martens are long-  
303 lived with both delayed breeding and implantation (Mead 1994), eliminating breeding female  
304 martens with established territories, similar to nesting birds in plowed fields, may have a  
305 disproportionate effect on viability than recruitment by juveniles (Grüebler et al. 2008).  
306 Alternatively, juvenile recruitment was identified as the most important population-level  
307 parameter in other marten populations, but limited resources were likely to constrain juvenile  
308 recruitment and population growth (Manlick et al. 2017). Enhancing connectivity to other marten



309 populations would provide a mechanism for juvenile recruitment and potentially mitigate  
310 concerns about genetic isolation of the central coast Oregon population but connectivity is likely  
311 severely limited for coastal populations in Oregon because of distance and barriers to movement  
312 (large rivers, human settlement) separating populations. Given that juvenile recruitment is  
313 unlikely to increase due to resource limits and population isolation, ensuring that other  
314 population parameters remain stable, such as adult survival, may be the most beneficial  
315 opportunity to maintain or increase population size.

316         Density of martens in the Oregon Dunes was nearly twice as high as estimates from other  
317 populations (Flynn & Schumacher 2009; Sirén et al. 2016). Similar to other carnivores, territory  
318 size is likely to be correlated with foraging resources (Kittle et al. 2015; Mattisson et al. 2016).  
319 We therefore predict that the smaller territories and higher densities we documented here were  
320 due to greater year-round foraging opportunities (e.g., over-wintering passerine birds; Eriksson  
321 2016; Nagorsen et al. 1989), and a favorable foraging environment. Specifically, we predict that  
322 dense vegetation mediates interactions with competitors and predators, and provides spaces to  
323 hunt and avoid predators similar to snow in winter (Andruskiw et al. 2008). Accordingly, the  
324 lack of martens inland, continued road kills along Highway 101, and evidence of previous  
325 breeding by adult females in our study provide circumstantial evidence that the Oregon Dunes  
326 functions as a refuge for martens. Moreover, coastal forests may have the potential to function as  
327 climactic refugium at low latitudes for martens (Channell & Lomolino 2000), particularly if  
328 winter snow pack limits habitat for marten populations in high-elevation montane forests  
329 (Halofsky et al. 2017; Spencer et al. 2015; Suffice et al. 2017).

330         The apparent absence of martens in inland late-seral forest and reserves indicate that  
331 these areas are not sufficient to conserve marten populations (Moriarty et al. 2016b). Whether

332 inland forest restoration can or should be applied to mimic the ecological conditions found in  
333 diverse young forest of the Oregon dunes demonstrates the complicated trade-offs in endangered  
334 species management, particularly because such restoration is most likely to occur on public lands  
335 in direct competition for resources used by Northern Spotted Owls. Ultimately, short-term  
336 management for coastal martens (i.e., next 40-years) appears relatively straightforward: maintain  
337 or increase habitat extent and limit human-caused mortalities.

### 338 **Conclusions**

339         Endangered species management inevitably comes with tradeoffs. In central coast  
340 Oregon, resource requirements for two similar sized predators with large spatial area  
341 requirements appear mutually exclusive, and current inland reserves appear inadequate for  
342 martens. Our snap-shot assessment of population size of Humboldt martens in central Oregon,  
343 and future projections using best available estimates for population growth, identified even a  
344 small amount of sustained human-caused mortalities may increase likelihood of population  
345 extirpation. Although population growth rate may be most sensitive to changes in juvenile  
346 recruitment, the near-complete isolation, limited resources, and lack of connectivity to other  
347 populations may mean that juvenile recruitment cannot be influenced through management.  
348 Influencing adult survival, through limits on human-caused mortalities may provide short-term  
349 benefits for this population. Endangered species management requires reliable estimates of  
350 population status and viability but long-term monitoring of population processes is needed to  
351 evaluate predictions of population viability and whether populations are declining (Caughley  
352 1994).

353

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358 for management-related discussions; and to the team that has incorporated martens into the  
359 updated Oregon Dunes Restoration Strategy.

360

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363

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505

**506 Table Captions**

507 Table 1. Input values for coastal marten viability analysis.

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

511 Table 3. Estimates of marten population size using spatial mark-recapture (SMR) and territory  
512 mapping. Both estimates were extrapolated from areas where we estimated density (northern  
513 study area; density = 1.02 km<sup>2</sup>; SMR), or radio-tracked martens (territory mapping). Male and  
514 female ratios for SMR assumed a ratio of 3.59 females per one male (estimated mean, Table 2).  
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519

520

**521 Figure captions**

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

529

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

541

542 Figure 3. We conducted a spatial mark-recapture study using remotely triggered cameras and  
543 Pacific marten (*Martes caurina*) with unique reflective markings on their collars in the northern  
544 portion of the coastal Oregon Dunes Recreation Area from 4 December 2015 to 12 January 2016.  
545 Here, we show a) location of all camera stations, b) stations which detected female martens, c)  
546 stations which detected male martens, and unmarked martens (large black dots), and d) an  
547 example of randomly generated female territory centers (squares) and coincident territorial  
548 outlines (dashed lines) used in territory mapping. For b and c, individual martens are depicted by  
549 unique colored dots (camera station detections), and outlines (outer boundary of territories).  
550 Imagery sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,  
551 USGS, AeroGRID, IGN, and the GIS User Community.

552

553 Figure 4. Technical articles that included the keywords “marten”, “density”, “territory”, and  
554 “home range”. Of the >75 papers reviewed for North American martens (*Martes americana*, *M.*  
555 *caurina*), four reported both home range sizes and density. Territories were estimated using  
556 either 100% Minimum Convex Polygons (MCP) or time-influenced Local Convex Hulls (t-  
557 LoCoH). Reported densities were either minimum known alive (MNKA) or calculated with  
558 spatial mark-recapture. Mean and 95% confidence intervals reported if available in the study.  
559 Other studies were conducted in Maine, USA which included estimates from three study areas  
560 (Payer and Harrison 1999), central British Columbia, Canada (Poole et al. 2004), New  
561 Hampshire, USA (Siren et al. 2016), and Quebec, Canada (Godbout and Ouellet 2010).

562

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

572

573 Figure 6. One-thousand density-dependent stochastic population projections (gray) for a  
574 subpopulation of Pacific marten (*Martes caurina humboldtensis*) from the theta-logistic model  
575 assuming a convex relationship between per-capita population growth and population size ( $\theta = 2$ )

576 ) beginning at three values of carrying capacity ( $K$ ; 20, 30, or 40), and three human-caused  
577 mortalities averaging 1, 2, or three marten annually. A  $\theta > 1$  may be more realistic for long-lived  
578 mammals, because the onset of density dependence likely occurs at higher population densities  
579 once crowding of territories occurs; assuming values where  $\theta > 1$  is less conservative because  
580 the population will be more permissive to mortality or other mortality. The mean population  
581 trajectory is given by the black line, and the red line signifies the pseudo-extinction threshold of  
582 two individuals. The proportion of trajectories falling below this threshold is the probability of  
583 extirpation  $\text{Pr}(\text{ext})$ . Within the next 40 years, stochastic mortalities averaging two or more  
584 marten lead to substantial extirpation risk, particularly for smaller values of  $K$ .

**Table 1** (on next page)

Input values for coastal marten viability analysis.

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1 Table 1. Input values for coastal marten viability analysis.

2

Variable	Value	Justification
Age at first parturition	2	Mead (1994)
Average number of kits/year ( <i>m</i> )	1.5	Anne and Schladweiler (1997), Flynn and Schumaker (2016) <sup>a</sup>
Survivorship to first parturition ( <i>la</i> )	0.35	
Kit survival (age 0-1)	0.49	Johnson et al. (2009)
Yearling survival (age 1-2)	0.7	Average for North American martens, McCann et al. 2010
Range of adult survival (age 2+)	0.7-0.9	McCann et al. 2010

3 <sup>a</sup>Anne and Schladweiler (1997) reported mean pregnancy rates of 85.5% and litter size of 2.6 for  
 4 martens in Montana, leading to an estimate of  $m = 1.1$ , and Flynn and Schumaker (2016)  
 5 observed pregnancy rates of martens in Southeast Alaska averaging only 47% over seven years  
 6 while litter size was 3.3, producing an estimate of  $m = 0.78$ .

**Table 2** (on next page)

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.



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

4

5

Annual Survival ( $e^{-M}$ )	Female kits per year ( $m$ )	Age of first parturition ( $a$ )	Survivorship to age at first parturition ( $l_a$ )	Maximum intrinsic growth rate ( $r$ )
0.7	1.5	2	0.35	0.143
0.8	1.5	2	0.35	0.205
0.9	1.5	2	0.35	0.268

**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<sup>2</sup>; 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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 4 female ratios for SMR assumed a ratio of 3.59 females per one male (estimated mean, Table 2).  
 5 Intervals are Credible intervals (SMR) and 95% confidence intervals (territory mapping).

Technique	Northern subpopulation		Southern subpopulation	
	Mean	Interval	Mean	Interval
Spatial mark-recapture	37.2	33.9–42.4	25.9	23.6–29.5
Females	26.8	24.5–30.6	18.7	17.0–21.3
Males	10.4	9.4–11.8	7.2	6.6–8.2
Territory mapping	40	25.6–50.4	33.8	20.4–41.4
Females	24	16.6–33.8	20.1	13.6–27.4
Males	16	9–16.6	13.7	6.8–14

6

7

**Table 4**(on next page)

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.

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

Parameter	Mean (SD)	Credible Interval		
		2.5	50	97.5
Density (per km <sup>2</sup> )	1.02 (0.09)	0.92	1.04	1.16
Abundance (# martens)	8.8 (0.76)	8	9	10
$\sigma_{\text{male}}$ (km)	1.14 (0.05)	1.06	1.14	1.24
$\sigma_{\text{female}}$ (km)	0.28 (0.01)	0.27	0.28	0.29
Sex ratio (females:males)	3.59 (1.23)	2	3.5	6.5
$\beta_0$ (intercept detection probability)	-1.6 (0.14)	-1.86	-1.6	-1.33
$\beta_1$ (sex effect on detection probability)	0.76 (0.19)	0.38	0.76	1.14
$\alpha_0$	-6.76 (1.68)	-9.7	-6.77	-3.59
$\alpha_1$ (canopy)	6.52 (4.56)	-2.14	6.27	15.83
$\alpha_2$ (canopy <sup>2</sup> )	-0.08 (4.14)	-8.67	0.06	8.02

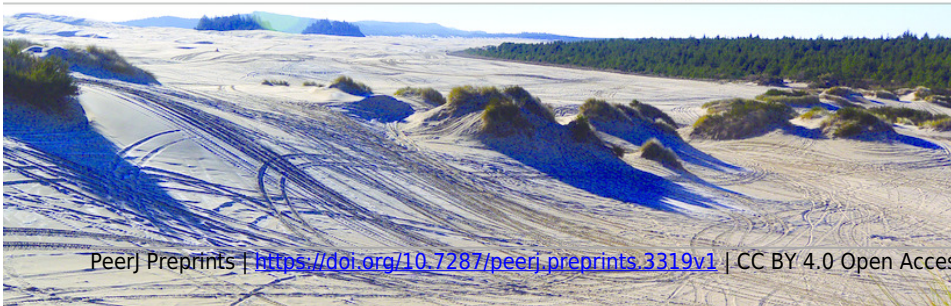
4

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# Figure 1

## 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.



## 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, Pennacook, 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. [html> D](#)

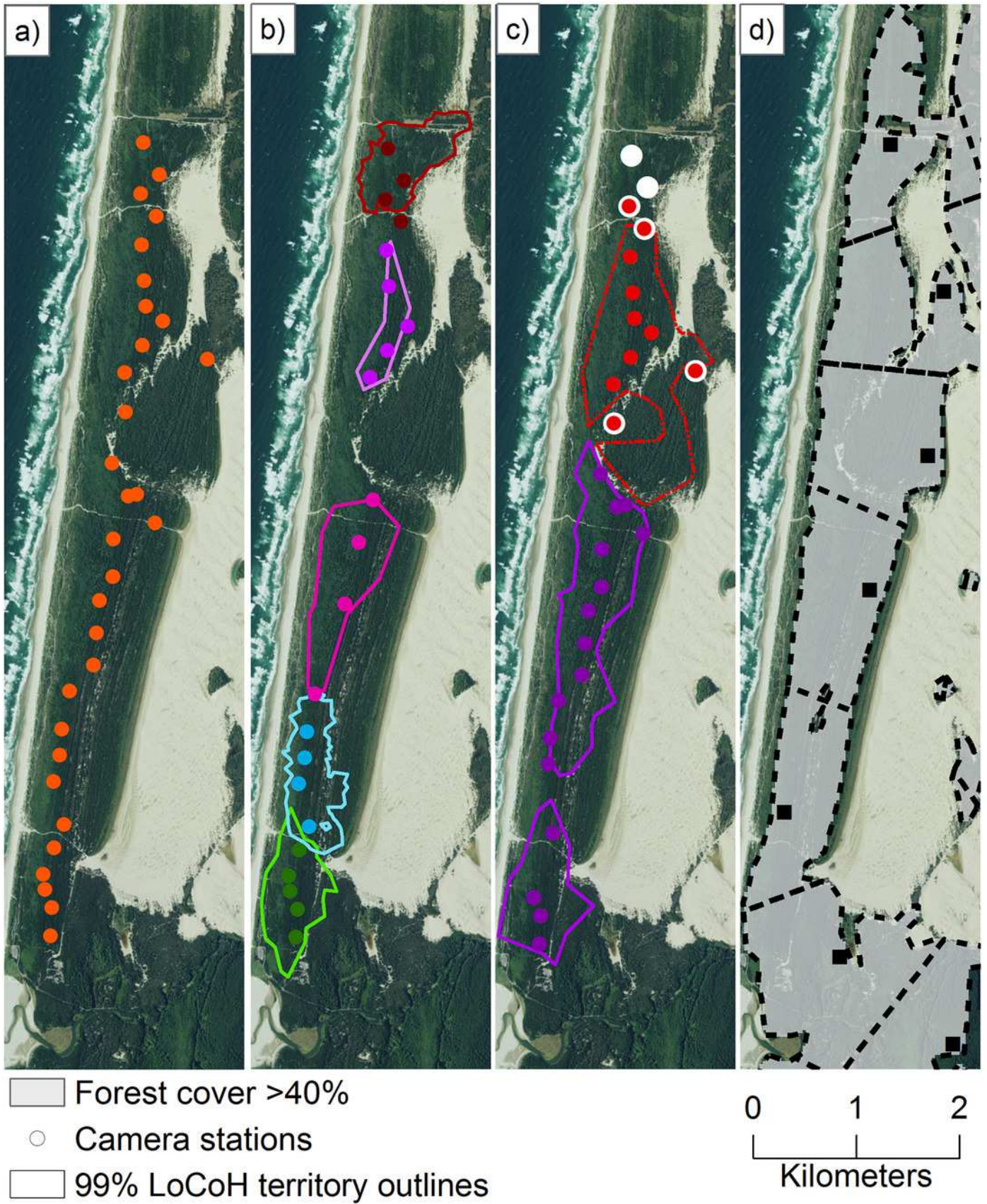




## Figure 3

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

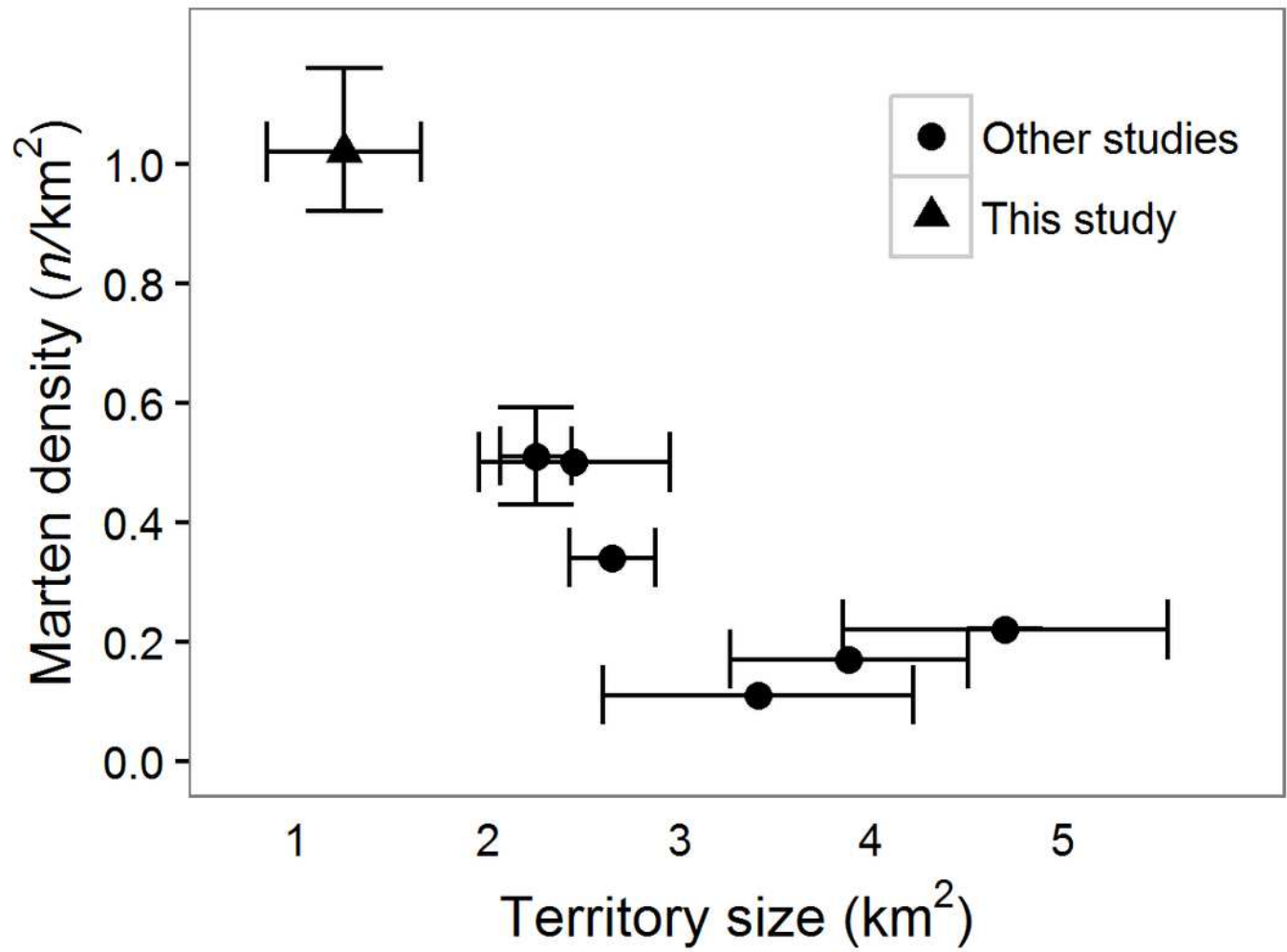
Figure 3. We conducted a spatial mark-recapture study using remotely triggered cameras and Pacific marten (*Martes caurina*) with unique reflective markings on their collars in the northern portion of the coastal Oregon Dunes Recreation Area from 4 December 2015 to 12 January 2016. Here, we show a) location 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.



## Figure 4

### North American marten densities and population sizes

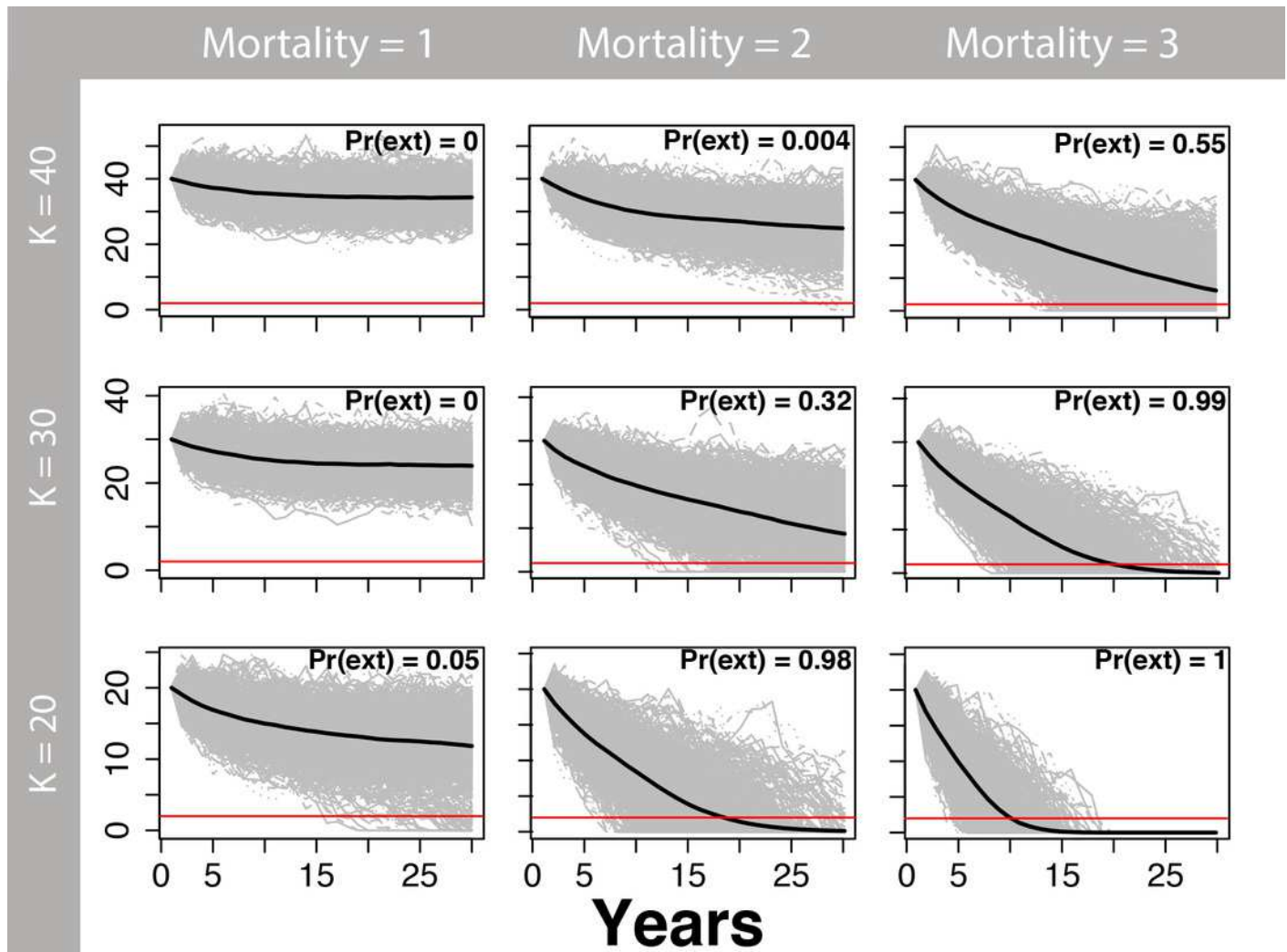
Figure 4. Technical articles that included the keywords “marten”, “density”, “territory”, and “home range”. Of the >75 papers reviewed for North American martens (*Martes americana*, *M. caurina*), four reported both home range sizes and density. Territories were estimated using either 100% Minimum Convex Polygons (MCP) or time-influenced Local Convex Hulls (t-LoCoH). Reported densities were either minimum known alive (MNKA) or calculated with spatial mark-recapture. Mean and 95% confidence intervals reported if available in the study. 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

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  $\Pr(\text{ext})$ . 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

Marten population viability analysis,  $\theta = 2$

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 ( $\theta = 2$ ) beginning at three values of carrying capacity (K; 20, 30, or 40), and three human-caused mortalities averaging 1, 2, or three marten annually. A theta value  $> 1$  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 a theta value  $> 1$  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  $\text{Pr}(\text{ext})$ . Within the next 40 years, stochastic mortalities averaging two or more marten lead to substantial extirpation risk, particularly for smaller values of K.



