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6 RH: Senzaki et al. • Off-site Impacts on Raptors' Breeding Success

7 **Predicting Offsite Impacts on Breeding Success of the Marsh Harrier**

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14 **ABSTRACT** Construction of buildings, and other types of land uses by humans can  
15 exert negative impacts on wildlife that live in the areas surrounding such developments  
16 (i.e., off-site impacts). To reduce or lessen such impacts, it is important to determine the  
17 biological metrics (e.g., abundance, breeding success) that are affected and at which  
18 spatial scales. We monitored the eastern marsh harrier (*Circus spilonotus*) breeding in  
19 wetland patches in northern Japan for 4 years and quantified its abundance (no. pairs) and  
20 breeding success (no. juveniles) in natural environments compared to artificial land uses  
21 in the surrounding areas. We developed a hierarchical model to simultaneously infer the  
22 effects of foraging habitats and artificial land uses on the numbers of pairs and juveniles.

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23 We found that the amount of foraging habitat within 0.5 km of wetland patches positively  
24 influenced the number of pairs per patch and that the amount of artificial land use within  
25 2.0 km from the patches negatively influenced the number of pairs per patch and the  
26 number of juveniles per pair. The number of juveniles per patch was therefore affected by  
27 these 2 features and was most susceptible to increased land use by humans within 2.0 km  
28 from the patches. Our results can be used to predict the magnitudes of off-site impacts on  
29 eastern marsh harriers before any additional development occurs. To effectively manage  
30 off-site impacts, we highlight the importance of considering species abundance and the  
31 biological processes mediating breeding success that are possibly affected by different  
32 land uses.

33 **KEY WORDS** abundance, hierarchical model, land-use change, off-site impacts, patch,  
34 reproductive success, spatial scale, wetland.

35 A primary cause of biodiversity loss worldwide is land use changes from a natural habitat  
36 to one dominated by human land use (i.e., on-site impacts; Jetz et al. 2007, Newbold et al.  
37 2015). Mitigation measures and the future consequences of such losses have been  
38 intensively studied (Fitzherbert et al. 2008, Newbold et al. 2015). In recent years,  
39 however, other threats to biodiversity associated with off-site impacts have been  
40 recognized (Raiter et al. 2014, Hastie et al. 2015). Off-site impacts are negative in nature  
41 and occur at sites remote from the location of the disturbance (Raiter et al. 2014). Such  
42 impacts have rarely been evaluated prior to development because it is difficult to predict  
43 where and when such impacts occur. Therefore, a systematic framework for predicting  
44 off-site impacts is needed (Raiter et al. 2014).

45 Human development (e.g., construction of artificial land uses) in areas surrounding

46 patches of breeding habitats has been one of the most common negative off-site impacts  
47 on breeding wildlife. Principal concerns are reduction in foraging areas (Mahan and  
48 Yahner 1999) and an increase in artificial land use in areas surrounding breeding habitats  
49 (Cardador et al. 2011, Quesnelle et al. 2015). Such increases can exacerbate the extent of  
50 human disturbance and the numbers of collisions of wildlife with buildings surrounding  
51 their breeding habitat, which may decrease the number of individuals and their breeding  
52 performance in breeding habitats (Chace and Walsh 2006, Loss et al. 2015). Therefore, to  
53 evaluate the magnitudes of off-site impacts on biodiversity prior to development, it is  
54 necessary to know how breeding wildlife in their habitat patches respond to reductions in  
55 foraging area and increases in artificial land uses in regions surrounding the habitat  
56 patches (Palomino and Carrascal 2007).

57 For effective management of off-site impacts, it is important to measure the extent to  
58 which off-site impacts degrade certain biological processes and identify the spatial scales  
59 at which the off-site impacts are severe. Biological processes operate across multiple  
60 spatial scales (Wiens 1989, Chalfoun and Martin 2007, Mahon et al. 2016). For example,  
61 abundance may not be positively correlated with another important metric, actual  
62 reproductive success (Van Horne 1983, Vickery et al. 1992). Similarly, the most  
63 influential land-use spatial scale in terms of reproductive success may not be appropriate  
64 in terms of abundance, because successful reproduction requires higher levels of  
65 resources or larger extents of habitat to compensate for the additional costs that  
66 reproduction imposes on adult survival (Nur 1984, Korpimäki and Rita 1996). However,  
67 few studies have considered the multiple biological processes possibly affected by  
68 different land uses at different spatial scales, especially in human-disturbed landscapes

69 (Schlaepfer et al. 2002, Battin 2004, Bock and Jones 2004).

70 The objective of our study was to explore whether abundance and reproductive  
71 success responded differentially to off-site impacts at different spatial scales. We  
72 surveyed the numbers of pairs and juveniles of a model species, the eastern marsh harrier  
73 (*Circus spilonotus*), breeding in wetland patches in the Yufutsu plain of northern Japan,  
74 and quantified breeding responses to changes in the extents of foraging habitat and  
75 artificial land uses in the surrounding areas. We selected the eastern marsh harrier for 2  
76 reasons: it is an endangered species in Japan, and thus a better understanding of the  
77 human impacts on this species is of prime importance (Japanese Ministry of the  
78 Environment 2012), and the species is a top predator in wetland ecosystems, and its  
79 presence or absence may alter predator-prey interactions that have ecosystem-wide  
80 consequences (Estes et al. 2011). Finally, to predict the expected off-site impacts on the  
81 harrier, we estimated the expected values of the number of pairs per patch and the  
82 number of juveniles per pair and per patch, in all wetland patches where harriers could  
83 potentially breed.

#### 84 **STUDY AREA**

85 We conducted field surveys on the Yufutsu plain, central Hokkaido, northern Japan (211.6  
86 km<sup>2</sup>, 42° 37'N, 141° 43' E). This area was dominated by natural wetlands and forests until  
87 the early 1900s. Approximately 90% of the wetlands and 50% of the forests have been  
88 lost to agricultural land and urban areas (M. Senzaki, Hokkaido University, unpublished  
89 data), and the remaining wetlands are fragmented. We defined continuities of the  
90 common reed (*Phragmites australis*), bluejoint reedgrass (*Calamagrostis langsdorffii*),  
91 and sedges (*Carex* spp) as wetland patches. We treated these vegetation cover types,

92 surrounded by other landscape features (e.g., forests, grasslands, cultivated land, paddy  
93 [rice] fields, industrial sites) extending for >50 m, as separate wetland patches (Senzaki  
94 and Yamaura 2016). The study area contained 97 wetland patches, ranging in size from 1  
95 ha to 101 ha. The study area had 20 solar power plants in 2015 covering 510 ha (M.  
96 Senzaki, unpublished data). More information on the study area is presented in Senzaki et  
97 al. (2015) and Senzaki and Yamaura (2016).

## 98 **METHODS**

### 99 **Study Species and Patch Selection**

100 The eastern marsh harrier is a medium-sized raptor species (length = 48–58 cm; Morioka  
101 et al. 1995). In our study area, the harriers arrive in late March and breed from early April  
102 to early August on a reed-bed in wetland patches. During the breeding period, they prey  
103 on small- or medium-sized birds and mammals outside of the breeding wetland patches  
104 (M. Senzaki, personal observation).

105         Based on our field observation of eastern marsh harriers, and on a previous study  
106 on the western marsh harrier (*Circus aeruginosus*; Cardador et al. 2009), the foraging area  
107 of breeding male eastern marsh harriers could extend to areas within an approximate 2-  
108 km radius of the nest. Therefore, to avoid spatial autocorrelation and pseudoreplication  
109 (Wiens 1989), we randomly selected 16 wetland patches (5.27–101 ha), the centroids of  
110 which were  $\geq 4$  km apart, as the study wetland patches. We used the centroids rather than  
111 the shortest distance between 2 given wetland patches, because harrier nests were  
112 observed in the interior of wetland patches.

### 113 **Harrier Breeding Surveys**

114 For harrier breeding surveys, we used the same monitoring procedure used in our

115 previous studies (Senzaki et al. 2015, Senzaki and Yamaura 2016). In summary, we  
116 conducted separate surveys of breeding attempts and subsequent breeding performance  
117 from April to mid-August, 2012–2015. In the breeding attempt surveys, we established  
118 observation points near each wetland patch and conducted 1–3 observational surveys  
119 between April and May of each year. Because we were not able to fully observe some  
120 wetland patches from a single observation point, we observed these patches from  
121 multiple observation points. During each observational period, we spent 2 hours  
122 observing harriers at each point. We determined whether each wetland patch had harrier  
123 pairs by observing any breeding behavior (i.e., nest-building, courtship feeding, feeding  
124 of chicks). We observed all wetlands 1–3 times on different dates (i.e., for 6 hr total if we  
125 did not detect harriers during the first or second observations). For the breeding  
126 performance surveys, we established additional observational points located  
127 approximately 200–300 m from the nests. We next conducted additional observations on  
128 5 occasions between mid-July and mid-August. We did not visit each nest to directly  
129 count the number of chicks because nest visiting can cause nest predation by mammalian  
130 predators (M. Senzaki, personal observation). During each observation, we stayed at each  
131 observational point for 3 hours. We considered the maximum number of juveniles we  
132 could count simultaneously as the number of juveniles for each pair. All surveys were  
133 performed in accordance with the relevant guidelines and regulations of the Japanese  
134 Ministry of the Environment and were conducted in accordance with current Japanese  
135 laws.

### 136 **Spatial Resolutions and Explanatory Variables**

137 Breeding western marsh harriers, the ecology of which is similar to that of the eastern

138 marsh harrier, forage intensively during nesting in areas within an approximately 2-km  
139 radius from the nest (Cardador et al. 2009). Thus, we calculated the proportions of  
140 foraging habitat and artificial land use within 0.5, 1.0, 1.5, and 2.0 km from the centroids  
141 of each patch using the 1:25,000-scale actual vegetation map of the sixth Japanese  
142 National Survey of the Natural Environment conducted by the Japanese Ministry of the  
143 Environment with the aid of ArcGIS version 10.0 (Environmental Systems Research  
144 Institute, Redlands, CA, USA). We defined all vascular plant communities (except  
145 forests) and pastures as foraging habitats (Morioka et al. 1995). We defined paved roads,  
146 urban and residential areas, industrial areas, and solar power plants as artificial land uses.  
147 We treated all of the different types of artificial land use as a single variable because all  
148 are unsuitable for harriers and there were only small numbers of each individual type of  
149 human development.

150       The amount of each type of land use at larger spatial extents was correlated with the  
151 amount with the same land use at smaller spatial extents. Thus, in terms of the extents of  
152 the artificial land use and the foraging habitat, we calculated correlation coefficients at  
153 different spatial extents and selected the combination of spatial scales showing the lowest  
154 correlation ( $r = 0.36$  and  $0.51$  for the artificial land use and foraging habitat, respectively;  
155 Figs. S1 and S2, available online in Supporting Information). Thus, we used variables  
156 derived from data acquired within 0.5 km and 2.0 km from the wetland patches in the  
157 following analyses.

158       To identify the final variables for inclusion in a hierarchical model dealing  
159 simultaneously with the numbers of pairs and juveniles, we constructed generalized linear  
160 mixed models (GLMMs) with Poisson errors for the numbers of pairs and juveniles

161 separately. The response variables were the number of pairs per patch and the number of  
162 juveniles per pair, respectively. We treated the aforementioned 4 variables as explanatory  
163 variables in each GLMM. Additionally, because larger wetland patches may harbor more  
164 pairs because of a positive area–abundance relationship (Yamaura et al. 2016), we treated  
165 log-transformed patch areas as an additional explanatory variable in the GLMM for the  
166 number of pairs. Because it is suggested that  $|r| < 0.7$  is an appropriate countermeasure to  
167 the problem of collinearity (Dormann et al. 2013), we confirmed that the correlations  
168 were low between these variables and the log-transformed patch area ( $r < 0.59$ ; Fig. 1).  
169 We used patch identity (ID) and the survey year as random variables in both GLMMs.  
170 These random variables can account for patch- and year-specific variance, respectively.  
171 In each GLMM analysis, we constructed models combining all possible explanatory  
172 variables and ranked them using Akaike’s Information Criterion for small sample  
173 situations ( $AIC_c$ ). We used the variables included in the best model (i.e., the model with  
174 the lowest  $AIC_c$ ) in the following hierarchical model. We conducted GLMM analyses  
175 using the lme4 (version 1.1-5) software (Bates et al. 2015) of R (version 3.0.2; R Core  
176 Team 2013).

### 177 **Hierarchical Model and Estimation of Abundance and Reproduction**

178 We developed the following hierarchical model enabling us to infer the effects of the  
179 explanatory variables selected in the GLMMs on the number of pairs per patch and the  
180 numbers of juveniles per pair and per patch. We assumed the number of observed pairs in  
181 patch  $i$  in year  $j$  ( $Np_{ij}$ ) to be a Poisson random variable:

$$182 \quad Np_{ij} \sim \text{Poisson}(\lambda_{ij}),$$

183 where  $\overline{p}_{ij}$  is the expected number of pairs in patch  $i$  in year  $j$ , modeled as a function of  
184 the explanatory variables as:

$$185 \quad \log(\overline{p}_{ij}) = \alpha_{int} + \alpha_k \times X_{ik} + \varepsilon_i + \varepsilon_j,$$

186 where  $\alpha_{int}$  is the intercept term,  $\alpha_k$  is a regression parameter of the explanatory variable  $k$ ,  
187 and  $X_{ik}$  is the  $k$ th covariate at patch  $i$ ;  $\varepsilon_i$  and  $\varepsilon_j$  are normally distributed random site and  
188 year effects added to account for unexplained heterogeneities among sites and years.

189 The number of observed juveniles per patch  $i$  in year  $j$  ( $Nj_{ij}$ ) was represented by a  
190 function of  $Np_{ij}$  and  $\overline{j}_{ij}$ , which is the expected number of juveniles per pair in patch  $i$  in  
191 year  $j$ . We assumed  $Nj_{ij}$  to be a Poisson random variable:

$$192 \quad Nj_{ij} \sim \text{Poisson}(\overline{j}_{ij} \times Np_{ij}),$$

193 where  $\overline{j}_{ij}$  is modeled as a function of explanatory variables as:

$$194 \quad \log(\overline{j}_{ij}) = \beta_{int} + \beta_k \times X_{ki} + \delta_i + \delta_j,$$

195 where  $\beta_{int}$  is the intercept term,  $\beta_k$  is a regression parameter of the explanatory variables,  
196 and  $X_{ki}$  is the  $k$ th covariate at patch  $i$ ;  $\delta_i$  and  $\delta_j$  are the normally distributed random site  
197 and year effects. Using  $\overline{j}_{ij} \times Np_{ij}$  to give the expected mean number of juveniles per  
198 patch, we set the  $Nj_{ij}$  values for patches without any pairs ( $Np_{ij} = 0$ ) to zero (i.e., the  
199 structural zero). The  $Nj_{ij}$  values for patches with nonzero pairs ( $Np_{ij} > 0$ ) could be  $\geq 0$  (the  
200 sampling zero) depending on the  $\overline{j}_{ij}$  and  $Np_{ij}$  values. Similar ideas have been recently  
201 used to accommodate detection histories given the occurrence or abundance of a focal  
202 species at sampling sites (Kéry and Royle 2016, Yamaura et al. 2016). Based on such  
203 serial formulation, we could separately model the numbers of pairs and juveniles as  
204 functions of different land uses in a single hierarchical model.

205 We estimated the parameters of the above models using a hierarchical Bayesian  
206 modeling framework and Markov chain Monte Carlo (MCMC) techniques (Royle and  
207 Dorazio 2008). We assumed the priors of each explanatory variable followed normal  
208 distributions with means of 0 and variances of 10,000. Similarly, we assumed random site  
209 effects followed non-informative uniform priors defined by [0, 5]. We obtained the  
210 posterior distributions of all parameters by performing 3 chain runs of 100,000  
211 simulations after a burn-in of 10,000, using JAGS version 3.3.0 ([http://mcmc-](http://mcmc-jags.sourceforge.net/)  
212 [jags.sourceforge.net/](http://mcmc-jags.sourceforge.net/), accessed 15 Mar 2016); we employed R (version 3.0.2) software (R  
213 Core Team 2013) and the package R2JAGS (version 0.03-11; [http://cran.r-](http://cran.r-project.org/web/packages/R2jags/)  
214 [project.org/web/packages/R2jags/](http://cran.r-project.org/web/packages/R2jags/), accessed 15 Mar 2016) to this end. We considered a  
215 model had converged if the  $\hat{R}$  values (Gelman–Rubin statistic) of all parameters were  
216 <1.1 (Gelman and Hill 2006).

217 We calculated the expected number of pairs per patch ( $\lambda_{p_{ij}}$ ) and the expected  
218 number of juveniles per pair ( $\lambda_{j_{ij}}$ ) and per patch ( $\lambda_{p_{ij}} \times \lambda_{j_{ij}}$ ) in wetland patches using  
219 estimates from the hierarchical model. We did not calculate such values for wetland  
220 patches of sizes <5.28 ha, which corresponded to the minimal patch area surveyed. Thus,  
221 we estimated these values for 48 wetland patches.

## 222 **RESULTS**

223 We identified 43 breeding pairs and 37 juveniles during the study period (Table 1). We  
224 observed ( $\bar{x} \pm \text{SD}$ ) 0.67  $\pm$  0.94 pairs per patch (range = 0–4,  $n = 64$  [16 observed patches  
225  $\times$  4 years]), 0.58  $\pm$  1.48 juveniles per patch (range = 0–7,  $n = 64$  [16 observed patches  $\times$  4  
226 years]), and 0.86  $\pm$  1.06 juveniles per pair (range = 0–3,  $n = 43$ ; Table 1). The correlation  
227 coefficient between the number of pairs and juveniles per patch was 0.72 ( $n = 64$  [16

228 observed patches  $\times$  4 years]).

229 Explanatory variables included in the best GLMMs were foraging habitat within  
230 0.5 km and artificial land use within 2 km for pairs per patch and the artificial land use  
231 within 2 km for juveniles per pair (Table 2). For each best model, we calculated marginal  
232 and conditional  $R^2$  values, which described the proportion of variance explained by the  
233 fixed factors only and by fixed and random factors, respectively (Nakagawa and  
234 Schielzeth 2013). The  $R^2$  values (marginal [conditional]) were 0.46 (0.58) for pairs per  
235 patch and 0.21 (0.54) for juveniles per pair, indicating that our best models had good fit.  
236 In terms of juveniles per pair, although the  $AIC_c$  differences between the best model and  
237 other models were relatively small, the effects of explanatory variables other than the  
238 artificial land use within 2 km included in subsequent models were weak (Table 2). Thus,  
239 in the hierarchical model, we decided to use the foraging habitat within 0.5 km and  
240 artificial land use within 2 km as explanatory variables for pairs per patch and the  
241 artificial land use within 2 km as the explanatory variable for juveniles per pair. The  
242 ranges of foraging habitat within 0.5 km and artificial land use within 2 km were 21–87%  
243 and 2–37%, respectively ( $n = 16$ ).

244 The hierarchical model showed that the number of pairs per patch was positively  
245 associated with the foraging habitat within 0.5 km and negatively associated with  
246 artificial land use within 2 km (Figs. 2a, d), although the effect of the artificial land use  
247 within 2 km was relatively weak because a small region of the 95% credible interval of  
248 the coefficient overlapped with zero (Table 3). The number of juveniles per pair was  
249 negatively associated with the artificial land use within 2 km (Fig. 2e, Table 3). Pairs per  
250 patch and juveniles per pair varied among sites and years; the fluctuations in the annual

251 numbers of juveniles per pair were especially large (Table 3). The number of juveniles  
252 per patch was affected by the foraging habitat within 0.5 km via the positive effect of that  
253 parameter on the number of pairs per patch and by the artificial land use within 2 km via  
254 the negative effect of that parameter on pairs per patch and on juveniles per pair (Fig. 2).  
255 Thus, juveniles per patch was more strongly affected by the artificial land use within 2  
256 km than were the other 2 metrics (Figs. 2d–f).

257         We estimated the expected values of all 3 harrier parameters in 48 wetland  
258 patches in our study area (Fig. 3). The expected number of pairs per patch in the current  
259 wetland patches was  $0.47 \pm 0.58$  ( $n = 48$  patches). The expected number of juveniles per  
260 pair was  $0.46 \pm 0.33$  ( $n = 48$  patches) and the expected number of juveniles per patch was  
261  $0.28 \pm 0.53$  ( $n = 48$  patches) in the current wetland patches.

## 262 **DISCUSSION**

263 To effectively avoid or lessen off-site impacts and other anthropogenic impacts on  
264 wildlife, it is important to evaluate the magnitude of such impacts on biological processes  
265 at various spatial scales. We surveyed how breeding harriers responded to the amount of  
266 foraging habitat and artificial land use in the surrounding areas. The number of harrier  
267 pairs per patch was reduced when the area of foraging habitat within 0.5 km of the  
268 wetland patch was reduced and when artificial land use increased within 2 km of that  
269 wetland patch (Fig. 2a, d). The number of juveniles per pair fell as artificial land use  
270 within 2 km increased (Fig. 2e). In terms of combinations of these relationships, we  
271 found that the number of juveniles per patch was most susceptible to the artificial land  
272 use within 2 km (Fig. 2f). Specifically, we showed that breeding pairs would disappear  
273 from wetland patches where the foraging habitat within 0.5 km was below 40% (Fig. 2a)

274 and when the artificial land use within 2 km approached 40% (Fig. 2d). We also showed  
275 that, irrespective of foraging habitat within 0.5 km, breeding pairs would produce no  
276 juveniles in wetlands where the artificial land use within 2 km was over 20% (Figs. 2e, f).  
277 The number of juveniles per pair in this study (0.86 juveniles/pair) was lower than the  
278 figure reported in another region dominated by natural grasses (1.8–2.8 juveniles/pair  
279 between years; Fefelov 2001).

280 The vulnerability of the numbers of juveniles per patch to the artificial land use  
281 within 2 km is important. The results suggest the establishment of an ecological trap in  
282 wetland patches where the artificial land use within 2 km is >20%. In other words,  
283 despite the strong correlation between the number of harrier pairs and the number of  
284 juveniles per patch, it is possible that a management strategy focused on the number of  
285 harrier pairs may be insufficient to ensure the long-term harrier persistence, even if the  
286 number of pairs is successfully maintained in the short-term by maintaining a minimum  
287 level of foraging habitat within 0.5 km and controlling amount of artificial land use  
288 within 2 km.

289 Moreover, the most influential spatial scales differed among the metrics (i.e., pairs  
290 per patch or juveniles per pair) that were considered (Tables 2, 3). Therefore, our work  
291 highlights that conservation managers should evaluate multiple biological metrics  
292 affected by different factors at different spatial scales, and that management of juvenile  
293 harriers in our study region should focus on the artificial land use within 2 km. However,  
294 these conclusions are based only on ecological perspectives. The economic costs and  
295 long-term feasibility of management plans must also be evaluated in the future (Cardador  
296 et al. 2015). In practice, conservation plans are often constrained by limited time and

297 funding (Lambeck 1997, Roberge and Angelstam 2004). Moreover, our results do not  
298 mean that land use in the area beyond 2.0 km from harriers' nests is unimportant.  
299 Although we used a 2-km radius as the maximum spatial scale, there may be breeding  
300 eastern marsh harriers within the wider foraging area. In such cases, to avoid off-site  
301 impacts, management of foraging habitat and artificial land use beyond a distance of 2  
302 km from nests may be required, although extending spatial scales for management may  
303 be more difficult because it would require restricting human activity in wider areas.  
304 Finally, although we included several types of artificial land uses in a single factor, each  
305 artificial land use type may have different impacts on harriers.

306       The impact of artificial land use within 2 km on the number of juveniles per pair can  
307 be explained by the negative impacts of human disturbance on juvenile survival, the  
308 hunting behavior of adult harriers, and adult harrier feeding rates when artificial land uses  
309 are present (Fernández et al. 1993, De la Torre et al. 2000, Rees et al. 2005, Arroyo and  
310 Razin 2006). Such impacts can occur throughout the entire foraging range and, hence,  
311 may also explain why the most influential spatial scale of artificial land use (i.e., 2 km)  
312 was larger than that of foraging habitat (i.e., 0.5 km). Similarly, high predation pressure  
313 upon intensification of human development may be, at least partially, responsible for the  
314 impact of artificial land use within 2 km on the number of juveniles per pair (Hethcoat et  
315 al. 2015). On the other hand, the strong effect of foraging habitat within 0.5 km on the  
316 number of pairs per patch may be explained by the fact that high prey availability in  
317 surrounding areas is of great importance when selecting breeding patches (Cornulier and  
318 Bretagnolle 2006). The large variance in the annual number of juveniles per pair may be  
319 explained by fluctuations in prey abundance, including the grey red-backed vole

320 (*Lethrionomys rufocanus*; Stenseth et al. 1996) or by differences in annual seasonal  
321 precipitation (Fisher et al. 2015). These results indicate that monitoring programs  
322 spanning several years are required to estimate the true impacts of environmental factors  
323 on wildlife (Magurran et al. 2010). In addition, the number of juveniles per pair had a  
324 weak relationship with foraging habitat within 0.5 km (Table 2). This is likely because  
325 harrier pairs might already select areas with greater proportions of foraging area.

326 Finally, we estimated the expected values of the 3 harrier parameters in 48 wetland  
327 patches in our study area (Fig. 3). These estimates can be used to predict the magnitudes  
328 of off-site impacts on harriers in each wetland patch before additional development  
329 begins or other land uses change.

### 330 **MANAGEMENT IMPLICATIONS**

331 The following management policies might be implemented to prevent predicted off-site  
332 impacts to eastern marsh harriers. To lessen impacts caused by a decrease in the foraging  
333 habitat within 0.5 km, offsets composed of suitable habitats, which compensate for  
334 habitat loss caused by development by generating ecologically equivalent gains  
335 elsewhere (Maron et al. 2012) may be appropriate. For example, changing non-foraging  
336 areas within 0.5 km of harrier breeding patches into foraging habitats may be effective,  
337 because grasslands converted from arable lands are important for foraging by the  
338 northern harrier *C. cyaneus* (Zuckerberg and Vickery 2006, Wilson et al. 2010). To lessen  
339 off-site impacts caused by an increase in the artificial land use within 2 km, it would be  
340 appropriate to avoid any additional development in areas within 2 km of harrier breeding  
341 patches (i.e., by separating development and conservation areas as much as possible).  
342 This option would be maximally effective when no development priority is evident near

343 wetland patches and where such patches are surrounded by undisturbed natural habitat  
344 (Benítez-López et al. 2010, Torres et al. 2016). Alternatively, because certain pairs still  
345 produced 2 juveniles under conditions of 20% artificial land use within 2 km (Fig. 2e), it  
346 is possible that site- or field-scale management focusing on the mechanisms underlying  
347 breeding failure, thus enhancing nest protection, might be effective (Santangeli et al.  
348 2014).

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515

516 **Figure captions**

517 **Figure 1**

518 Correlation coefficients for the relations among proportion of foraging area (FA),  
519 proportion of artificial land use (AL), and patch areas at different spatial extents for  
520 patches of eastern marsh harrier habitat in northern Japan, 2012–2015. The terms 0.5\_AL  
521 and 2.0\_AL refer to the extent of artificial land use within buffered distances of 0.5 km  
522 and 2 km, respectively, from the estimated (gravity) center of survey patches. Similarly,  
523 the terms 0.5\_FA and 2.0\_FA refer to the extent of foraging habitat within buffered  
524 distances of 0.5 km and 2 km, respectively, from the estimated (gravity) center of survey  
525 patches. Histograms on the diagonal represent the frequency distribution of each variable.

526

527 **Figure 2**

528 The upper 3 boxes indicate the effects of the percentage of foraging area (FA) within 0.5  
529 km of the wetland patches on the number of harrier pairs per patch (a), the number of  
530 juveniles per pair (b), and the number of juveniles per patch (c) for eastern marsh  
531 harriers, northern Japan, 2012–2015. The 5 lines in each box were derived using the  
532 hierarchical model; the various degrees of shading indicate differences in percentage of  
533 artificial land use within 2 km, in descending order of darkness (2%, 10%, 20%, 30%,  
534 and 37%). The bottom 3 boxes indicate the effects of the percentage of the artificial land  
535 use (AL) within 2 km of the wetland patches on the number of harrier pairs per patch (d),  
536 the number of juveniles per pair (e), and the number of juveniles per patch (f). All lines  
537 were derived using the hierarchical model, and the 5 different shadings employed in  
538 boxes (d) and (f) indicate differences in percentage of foraging area within 0.5 km in

539 descending order of darkness (87%, 80%, 60%, 40%, and 21%). The gray circles are  
540 actual values from field surveys.

541

542 **Figure 3**

543 The expected numbers of pairs per patch (a), the number of juveniles per pair (b), and the  
544 number of juveniles per patch (c) in terms of a combination of the percentage of foraging  
545 area (FA) within 0.5 km and the percentage of artificial land use (AL) within 2 km (solid  
546 lines) for eastern marsh harriers, northern Japan, 2012–2015. Only the number of  
547 juveniles per pair (b) varied depending on the value of a single factor (AL within 2 km).  
548 Gray circles indicate all potential breeding wetland patches in the study area ( $n = 48$ ).

549 Table 1. Results of the eastern marsh harrier breeding survey, northern Japan, 2012–2015. In each year, we monitored 16 wetland  
 550 patches.

Metric	Year									
	2012		2013		2014		2015		Total	
	$\bar{x}$	SD								
Pairs (no.)	11		10		12		10		43	
Juveniles (no.)	8		14		14		1		37	
Pairs/patch	0.69	0.87	0.63	0.98	0.75	1.13	0.63	0.89	0.67	0.94
Juveniles/patch	0.50	1.1	0.88	1.75	0.88	2.09	0.06	0.25	0.58	1.84
Juveniles/pair	0.73	0.90	1.40	1.26	1.17	1.11	0.10	0.32	0.86	1.06

551  
 552

553 **Table 2.** Results of generalized linear mixed models of number of pairs per patch and number of juveniles per pair for eastern marsh  
 554 harriers in wetland patches, northern Japan, 2012–2015. We show all models with differences in corrected Akaike’s Information  
 555 Criterion ( $\Delta AIC_c$ ) < 2. Weight is the Akaike weight.

Response variable	Coefficient ( $\pm$ SE)						$\Delta AIC_c$	Akaike weight
	Intercept	Patch area	Foraging habitat within 0.5 km	Artificial land use within 0.5 km	Foraging habitat within 2 km	Artificial land use within 2 km		
Pairs/patch	–1.26 (0.39) **		1.14 (0.36) **			–0.70 (0.34) *	0.00	0.18
	–1.34 (0.45) **		1.26 (0.45) **				1.68	0.08
	–1.20 (0.36) ***	0.88 (0.25) ***			0.88 (0.37) *		1.76	0.08
	–1.36 (0.41) ***	0.71 (0.21) ***		–0.69 (0.44)	1.06 (0.48) *		1.93	0.07
	–1.29 (0.39) ***		1.09 (0.35) **		0.26 (0.36)	–0.67 (0.33) *	1.95	0.07
Juveniles/pair	–0.50 (0.49)					–0.67 (0.24) **	0.00	0.30
	–0.62 (0.50)				0.54 (0.46)	–0.87 (0.36) *	0.63	0.22
	–0.52 (0.50)		–0.20 (0.19)			–0.70 (0.24) **	1.49	0.14

556 \*, \*\*, and \*\*\* indicate significance levels  $P < 0.05$ ,  $P < 0.01$ , and  $P < 0.001$ , respectively.

557

558 **Table 3.** Estimated parameters for a hierarchical model seeking to explain adult and juvenile numbers of eastern marsh harriers in  
 559 wetland patches where breeding occurred, northern Japan, 2012–2015. Successful convergence was evident based on  $\hat{R}$  values (all <  
 560 1.1). “Site” and “Year” were treated as random effects.

Model parameters	Coefficient					$\hat{R}$
	$\bar{x}$	SD	95% credible intervals			
			Lower	Median	Upper	
<b>Pairs/patch</b>						
Intercept	-5.033	2.391	-10.764	-4.686	-1.281	1.001
Foraging habitat within 0.5 km	0.079	0.034	0.026	0.074	0.161	1.002
Artificial land use within 2 km	-0.099	0.068	-0.252	-0.094	0.023	1.003
Site	1.347	0.694	0.364	1.213	3.097	1.004
Year	0.312	0.429	0.008	0.187	1.453	1.008
<b>Juveniles/pair</b>						
Intercept	0.190	1.13	-2.235	0.19	2.493	1.003
Artificial land use within 2 km	-0.108	0.061	-0.238	-0.108	-0.008	1.004
Site	0.554	0.526	0.028	0.416	1.969	1.000
Year	1.669	1.028	0.348	1.405	4.304	1.001

561  
562

563 Article Summary:

564 We quantified how eastern marsh harriers breeding in wetland patches responded to the amount of foraging habitat and artificial land  
565 use in the surrounding areas. Our results showed that the number of juveniles per patch was most susceptible to the artificial land use  
566 within 2 km of the wetland patches via direct impacts of artificial land use on the number of juveniles per pair and indirect impacts on  
567 the number of pairs per patch.

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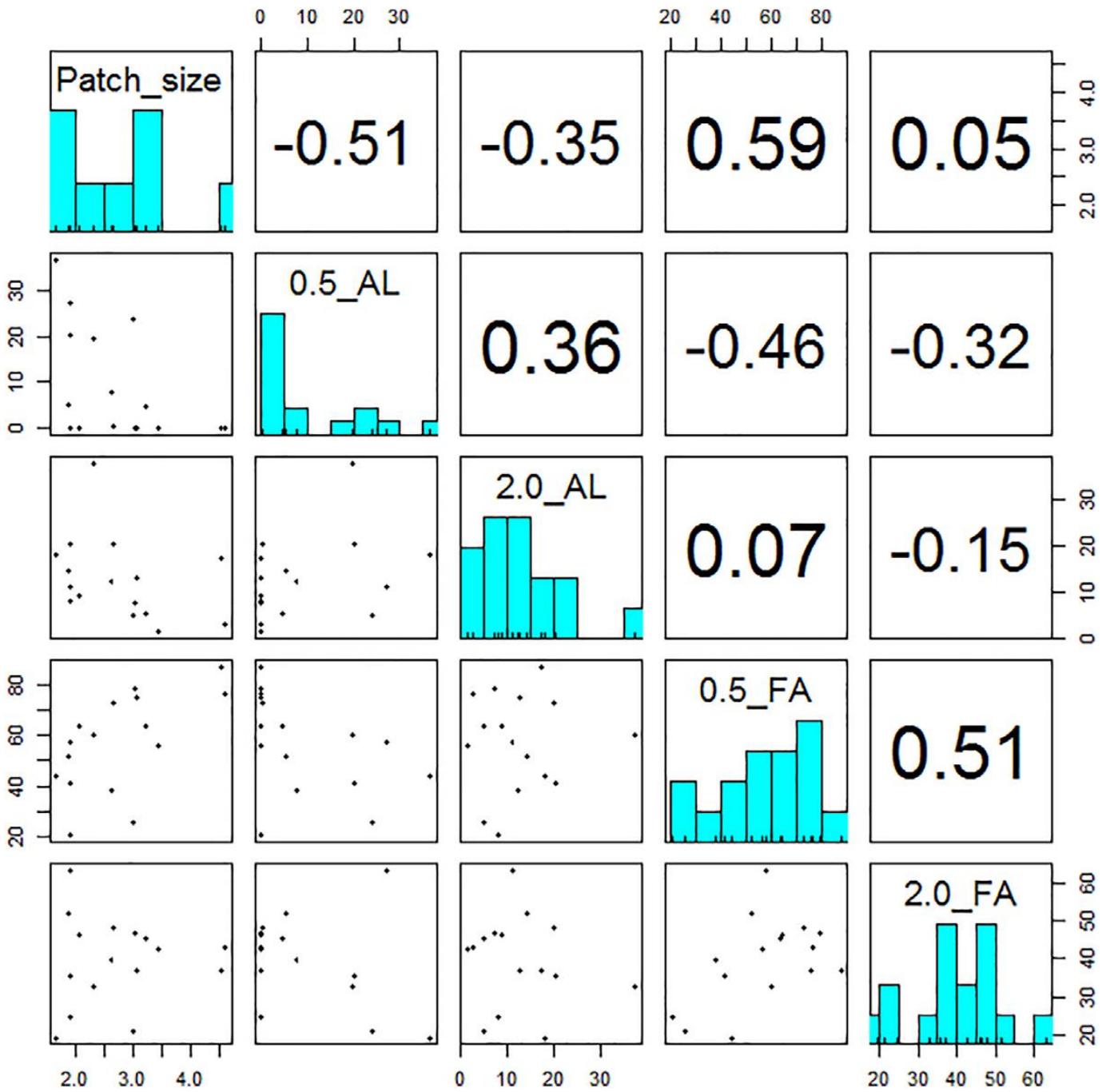
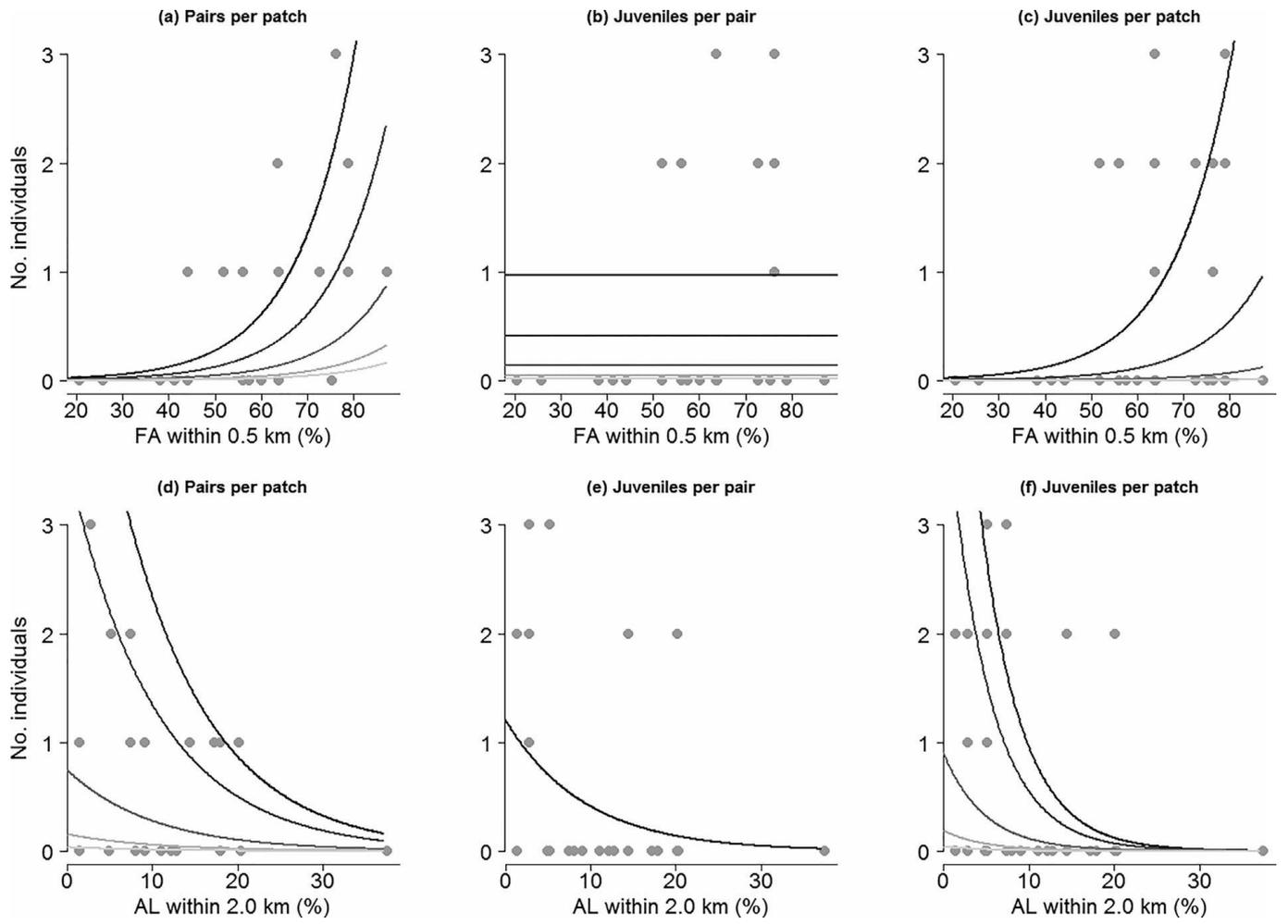
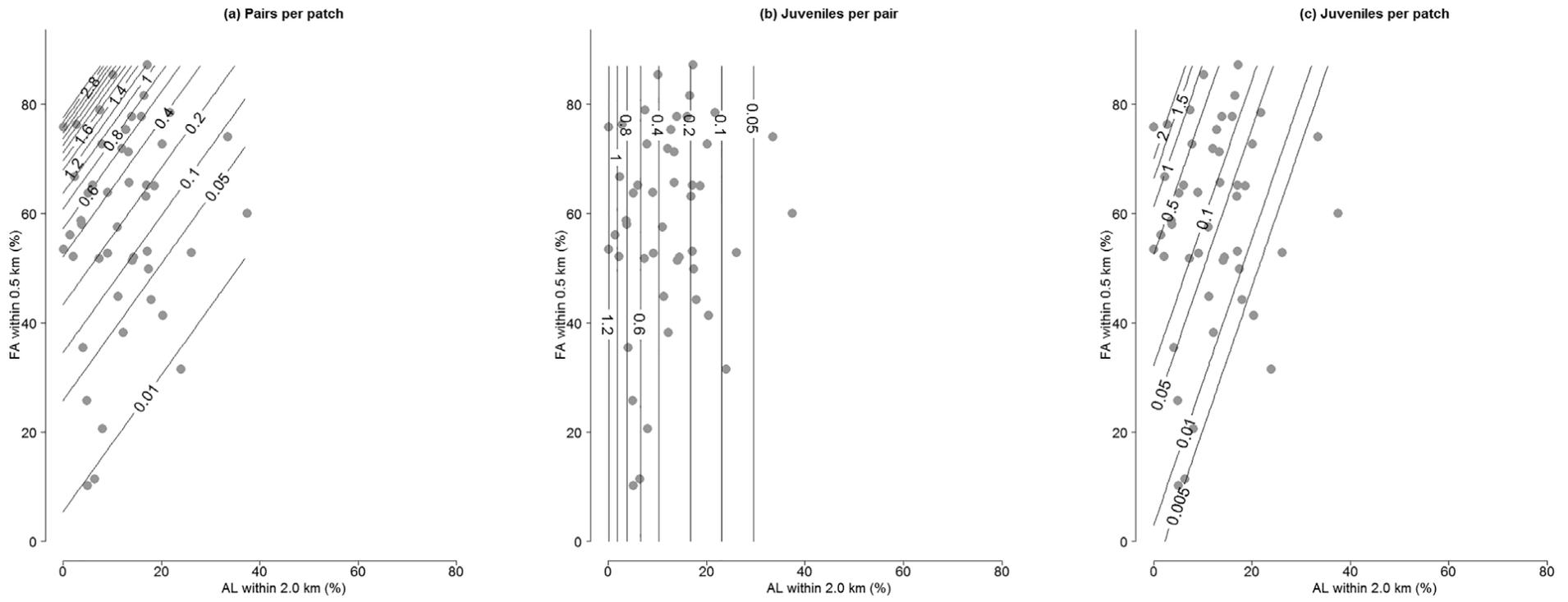


Figure 1



**Figure 2**



**Figure 3**