# Animal Conservation

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## Landscape-scale effects of single- and multiple small wind turbines on bat activity

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Manuscripts

1  **Landscape-scale effects of single- and multiple small wind turbines on bat activity**

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## ABSTRACT

While the effects of wind farms on bats are widely studied, effects of small wind turbines (SWTs, here <25m hub height) remain understudied. SWTs are installed in a wider range of habitats compared to wind farms and their effect on wildlife can therefore be different. While single SWTs can adversely affect bat activity in their immediate vicinity, they are often installed in clusters, and to date no data are available on whether installation of more than one turbine increases the likelihood of adverse effects on bats.

Here, we test whether (1) SWT installations affect the activity of two species of bat (the common pipistrelle *Pipistrellus pipistrellus* and soprano pipistrelle *P. pygmaeus*) on a landscape scale (here defined as up to 500m from SWTs) and (2) such an effect is stronger when multiple (2-4) SWTs are installed. We show that, after accounting for potentially confounding effects (e.g. variation in habitat and weather), (1) mean *P. pipistrellus* activity is lower at 0-100m compared to 200-500m from SWTs, and (2) the effect on *P. pygmaeus* activity tends to be similar and stronger in multiple SWT sites, although evidence for the latter is limited.

We conclude that in some cases, adverse effects of SWTs on bat activity may be measurable over longer spatial scales (within 100m) than previously thought. However, combined with earlier findings, it is likely that the bulk of such effects operate within relative close proximity of SWTs (<25m). Moreover, although these effects may be species-specific, with e.g. *P. pygmaeus* potentially more strongly affected by multiple SWT sites, this requires further data. These findings are highly relevant to decision-making aimed at minimizing any adverse effects of wind turbines, specifically single- vs. multiple SWT developments, on wildlife.

36    **KEY WORDS:** cumulative effects, microturbines, domestic turbines, renewables, renewable

37    energy, conservation, planning

38    **INTRODUCTION**

39    Understanding and predicting how wildlife is affected by disturbance or habitat loss is becoming

40    increasingly important as anthropogenic pressures on the natural world continue to grow

41    (Tuomainen & Candolin 2011). This is particularly pertinent where incremental changes or

42    disturbances could combine to produce disproportionally greater (adverse) effects. For example,

43    whilst the rapid growth of the wind energy sector worldwide provides a vital contribution to

44    sustainable energy production, a growing number of studies show that wind farms can have

45    adverse effects on wildlife (Kuvlesky *et al.* 2007, Zwart *et al.* 2015), both directly through

46    collision mortality (e.g. Rydell *et al*. 2010) and indirectly through disturbance or displacement

47    effects (e.g. Pearce-Higgins *et al*. 2009). Moreover, wind farms with larger numbers of turbines

48    installed can have greater effects on wildlife compared to smaller sites, even if e.g. collision risk

49    per turbine is relatively low (Langston & Pullan 2003, Zwart *et al.* 2015).

50    By contrast, similar effects of small wind turbines (SWTs) on wildlife remain relatively

51    unknown. These turbines are not only much smaller in size (in the UK, typical units are between

52    6 and 25m hub height) than those in wind farms, they are also commonly installed in a much

53    wider range of habitats. Thus, their impacts on wildlife are likely to be different to that of large

54    turbines, but up until recently this had not been quantified systematically. In addition to direct

55    mortality (Minderman *et al.* 2014), our previous work found evidence for adverse effects of

56    SWTs on bat activity (e.g. avoidance behaviour, Minderman *et al.* 2012). Whilst this is likely to

57    lower the risk of collision, such avoidance behaviour could have important population-level

58    consequences in itself, as it can amount to effective habitat loss (Minderman *et al.* 2012).

59    However, these previous studies focused on a relatively limited spatial scale (e.g. within 25m of

60    installed SWTs) and on single SWTs only. Crucially, it is therefore unclear whether any such

61    adverse effects of SWTs on wildlife could be greater at sites with more than one turbine

62    installed, i.e. whether the installation of multiple SWTs causes a disproportionally greater effect.

63    This lack of understanding of the potential disproportionate effects of sites with multiple SWTs

64    is particularly important for two reasons. First, the number of SWTs installed is growing rapidly

65    with over 900,000 units installed worldwide by 2014 (compared to 656,000 in 2010) and this

66    growth is set to continue (Pitteloud and Gsänger 2016). Secondly, SWTs are increasingly being

67    installed in groups, for example between two and four turbines in close proximity. Indeed, some

68    companies specifically promote the installation of multiple SWTs to maximize yield and

69    eligibility for government grants or payback schemes. As a result, where SWT installation

70    requires planning permission (Park, Turner & Minderman 2013), decision makers are

71    increasingly asked to decide whether multiple-turbine installations would have greater effects on

72    wildlife, or if limiting the number of SWTs to be installed would be an effective mitigation

73    option. Currently, the evidence base for such decisions for SWTs specifically is entirely lacking.

74    Here, we aim to (1) quantify the effect of SWTs on bat activity (and thus concomitant habitat

75    loss) on a wider landscape scale, up to 500m from installed turbines (as opposed to 25m in

76    Minderman *et al*. 2014), and (2) to test whether this effect is different between single- and

77    multiple (2-4) turbine installations.  Using data collected at 34 SWT sites throughout the UK we

78    test the following predictions: (1) bat activity is systematically lower in closer proximity (e.g. 0-

79    100m from SWTs compared to 100-200m, 200-300m, etc.) of operating SWTs, controlling for

80    the effects of habitat and environmental conditions; and (2) the effect of SWT proximity on bat

81    activity is stronger in sites with multiple (2-4) SWTs installed compared to single SWT sites.

82

**METHODS**

**Sites**

85    Data were collected at 34 SWT sites in central and eastern Scotland. Sites were selected from an

86    existing database of owners (Minderman *et al.* 2012; Park, Turner & Minderman 2013) based on

87    how representative they were of common UK SWT installation settings in terms of habitat,

88    turbine models and size. All turbines studied here were free-standing and between 6 and 25m

89    (mean 16m, 75% of sites had turbines between 15 and 18m; including hub height in the analyses

90    presented here does not affect results or conclusions – see Supplementary Material) in hub

91    height, and all were in rural settings but specific habitat in the surrounding area varied (see

92    Habitat data and variable selection). The number of SWTs installed in each site varied between

93    one and four (median 1.6) and the distance between individual turbines in a site was between 12

94    and 90m (with only one site >62m and a mean of 46.4m). SWTs installed in individual sites were

95    the same size and specification with the exception of one site. More than two SWTs were

96    installed in only five sites in our sample. We therefore restricted the analyses presented here to a

97    comparison of single and multiple turbine sites; hence we here refer to sites with 2-4 SWTs

98    installed as "multiple turbine" sites throughout the remainder of this manuscript. Although this

99    limits possible inference from our findings somewhat, we are confident that this reflects the

100    current distribution of numbers of turbines per site in the UK; i.e. the majority of sites have one

101    or two SWTs installed (*pers. obs.*).

**Bat data and transects**

103    Bat activity data were collected between 28 May and 1 September 2013 and 7 July and 4

104    September 2014. This period reflects the seasonal activity of the species studied here (Swift

105    2009). The time of data collection varied but started 30 minutes after sunset at the earliest and

106    finished at least 60 minutes before sunrise in all cases.

107    Bat activity was measured along transects by 1-2 observers walking the length of each transect at

108    a slow (approximately 2.5 km h$^{-1}$) and constant pace, using EchoMeter EM3+ bat detectors

109    (WildLife Acoustics, Mass., USA). A target of four transects was planned for all sites, running

110    out from the turbine (or the central point between turbines in the case of multiple turbine sites) in

111    four directions. However, because of physical constraints (e.g. walls, impassable fences or

112    ditches, houses or buildings) the actual number of transects per site as well as their length varied

113    (3-4 transects, mean 3.7 per site, length: 300-500m). All transects were placed using a

114    combination of GIS-based planning and on-site assessment of landscape variation, so that (1) the

115    combination of all transects within each site covered all major habitats present, and (2) the

116    overall distance separating each transect was maximized. Transects were divided into 100m

117    sections running out from the turbine centre point, giving up to five distance bands running away

118    from the turbine. See Figure A1 for an example transect and transect section layout.

119    One measure of ground level wind speed was taken at the end of each section (i.e. in each

120    distance band) on each survey visit using handheld anemometers. Minimum daily temperature

121    measures for each survey visit were obtained from the UK MIDAS weather station data at

122    Grangemouth (N 56° 1' 5.15, W 3° 43' 5.88, between 5.5 and 92.6 km, average 52.4km, from the

123    sites) (UK Meteorological Office 2006).

124    **Habitat data and variable selection**

125    To account for expected confounding effects of habitat variation on bat activity we collated

126    measurements of habitat availability per transect section. To do this, we placed 50m buffers

127    around digital maps of each transect route, resulting in approximately 100m x 100m transect

128    sections. The exact area of each section varied because of non-linear transect sections, but this

129    was accounted for in the analysis, see Statistical analysis and Figure A1. All habitat variables

130    were quantified in each transect section using 1:1250 UK Ordnance Survey MasterMap

131    Topography digital maps, using QGIS v. 1.8 (http://www.qgis.org/en/site/). We focused on two

132    key measures of habitat variability in each transect section. These two variables were selected on

133    the basis of a preliminary analysis (See Supplementary Material) of the effect of a full set of 10

134    habitat variables on bat activity. This was done to avoid both overparameterisation of the models,

135    as well as the inclusion of highly collinear habitat metrics. First, we used **edge density** ($m\ m^{-2}$)

136    as a measure of the density of "edge" habitat (defined as woodland and water edges, hedgerows,

137    roads and tracks, roadsides, field boundaries and building edges), calculated as the total length of

138    all such features divided by the area of the transect section. Although the specific effect of these

139    pooled habitat features on bat activity may vary, all tend to be associated with high levels of bat

140    activity relative to open and/or homogenous habitat (e.g. through their use as commuting routes)

141    (Walsh & Harris 1996). Second, we used the **proportion of woodland** calculated as the sum of

142    all tree coverage ($m^2$) (coniferous, non-coniferous and unclassified trees) divided by the transect

143    section area.


144    **Data analysis and statistics**


145    *Bat activity: probability of a pass per hectare surveyed*

146    Bat activity was initially quantified as the number of bat passes (defined as a sequence of at least

147    two "search-phase" echolocation calls separated by less than a second) per transect section.

148   However, we chose to analyse our data as bat activity presence or absence per transect section,

149   per survey visit, because the distribution of observed counts was highly skewed (many zeros and

150   excessive variation) so that count-based statistical models did not provide any reasonable fit.

151   Thus, throughout the remainder of this paper, bat activity is measured as the probability of at

152   least one bat pass per unit area. Foraging calls ("buzzes") were recorded in some cases, but in too

153   small numbers to be included in the analysis presented here. In addition, because the area

154   covered by each transect section varied slightly (see Bat data and transects), we here model the

155   probability of detecting bat activity per hectare surveyed within each section.

156   *Statistical analysis*

157   We used generalized linear mixed effects models (GLMMs) (Gelman & Hill 2007) to analyse

158   our data.

159   *Model structure*

160   We constructed two models for bat activity; one *P. pipistrellus* and one for *P. pygmaeus* activity.

161   The structure of both models was the same. In each case, activity was modelled as the probability

162   of a bat pass per unit area on a given survey visit as the response variable with a GLMM with

163   binomial errors and a complementary log-log link function (*clog-log*). This link function allowed

164   us to include transect section area as an offset in the model on the appropriate scale (Agresti

165   2013). In turn, this offset accounts for slight variation in the size of each transect section (see Bat

166   data and transects and Figure A1), modelling probability of a bat pass per unit area. To account

167   for the non-independence of repeated measurements from the same site and transect sections, all

168   models included transect nested within site as a random effect. To test our two predictions (see

169   Introduction), we included two focal fixed factors; (1) transect section (distance bands; 0-100m,

170   100-200m, 200-300m, 300-400m and 400-500m from the SWTs) and (2) turbine number (single

171    or multiple SWTs), as well as the interaction between the two. In addition to these focal factors

172    we included the two selected habitat variables (edge density and proportion of woodland; see

173    Habitat data and variable selection) as continuous covariates. Moreover, because bat activity is

174    known to vary with weather conditions (particularly temperature and wind speed), across the

175    season and through the night, we also included covariates for the minimum temperature over 24

176    hours (°C), wind speed (m s$^{-1}$), day number (1 January = 1), time to midnight (minutes, with

177    negative and positive values indicating before and after midnight respectively) and time to

178    midnight$^2$ (to account for potential non-linear effects of the latter). Finally we included year as a

179    factorial predictor to account for potentially systematic differences in bat activity between the

180    two years of the study. Thus, accounting for any confounding effects of habitat and

181    environmental conditions, a transect section effect would indicate a systematic difference in bat

182    activity as a function of distance from SWTs (Prediction 1), and an interaction between this and

183    turbine number would indicate that the strength of this effect depends on the number of SWTs

184    installed (Prediction 2).

185        To avoid overparameterisation of the models, interactions other than those specified

186    above (i.e. between confounding effects) were not considered. All inputs were standardised

187    (centred to 0 and scaled to 1 SD) to improve performance of parameter estimation and to allow

188    direct interpretation of relative effect sizes. Marginal and conditional $R^2$ were presented as

189    measures of model fit (Nakagawa & Schielzeth 2013). We calculated and presented model

190    predictions on the response (measured) scale. Summary statistics of unstandardised model inputs

191    are given in Table A1.

192    *Model predictions and interpretation*

193    We chose to present full models only, to avoid issues with any form of model simplification

194    (Cade 2015, Whittingham *et al.* 2006). We interpreted the model outputs through assessment of

195    (1) relative effect sizes using standardised inputs, and (2) 95% quantiles of predictions of the

196    response at each of the levels of interest (specifically the number of turbines and distance band)

197    at average values for the remaining coviariates. The 95% quantiles of predicted distributions

198    were made using N = 1000 bootstrap simulations (generating new values of both the "spherical"

199    random effects and the independent errors in each run) of parameter estimates of each model.

200    We used R version 3.1.3 (http://cran.r-project.org/) for all statistical analyses including, in

201    particular package *lme4* (Bates *et al.* 2014), to fit GLMMs, and its bootMer() function to produce

202    parametric bootstrap samples..

203

204    **RESULTS**

205    Over the two years of the study, we collected bat activity data in N = 1395 transect sections,

206    during 78 survey visits. Most sites (N = 30) were surveyed on at least two occasions (2-6 surveys

207    per site), but four sites were only visited once. Within this sample, N = 20 were single-turbine

208    sites, and N = 14 were multiple-turbine sites (2-4 turbines). In total, we recorded N = 1867 bat

209    passes, of which 98.4% (N = 1838) were *Pipistrellus* spp. (N = 969 [51.9%] *Pipistrellus*

210    *pipistrellus*, N = 714 [38.2%] *P. pygmaeus*, and N = 155 [8.3%] *Pipistrellus* sp.). The remaining

211    1.6% of total calls recorded were a mixture of *Nyctalus noctula*, *Plecotus auritus* Linnaeus and

212    *Myotis* spp., but because these species combined comprised N = 29 calls, here we focus on

213    analyses of *Pipistrellus* spp. activity. Overall, *Pipistrellus* bat activity was detected on 466

214    section surveys.

215    Parameter estimates for the models for *P. pipistrellus* and *P. pygmaeus* are presented in Table 1.

216    In terms of confounding effects, there were strong non-zero effects of wind speed (negative),

217    edge density (positive) on the activity of both species, as well as an effect of time to midnight

218    (linearly negative for *P. pipistrellus* and quadratic for *P. pygmaeus*). In addition, both the

219    proportion of woodland present and day number affected *P. pygmaeus* activity positively, and *P.*

220    *pipistrellus* activity was higher in 2014 compared to 2013.

221    Accounting for these effects of environmental and habitat variables, we find some evidence for

222    an effect of turbine proximity. Specifically, this effect is strongest for *P. pipistrellus* (Table 1a),

223    for which activity in distance band 1 (0-100m, intercept in Table 1a) is lower than the activity in

224    distance bands 2-5 (100-500m). Based on parameter estimates and their errors, no such effect of

225    turbine proximity is evident in the model for *P. pygmaeus* activity (Table 1b). Moreover, again

226    based on parameter estimates alone, there is no evidence for an interaction between distance

227    band and number of turbines installed.

228    This interpretation of coefficient estimates above is largely mirrored by assessment of the

229    predicted levels of activity, although a strong suggestion of an interaction with the number of

230    turbines installed is evident (Figure 1). Predicted activity is lowest for both species in distance

231    band 1 (0-100m). In particular, for both species, at multiple SWT sites the predicted mean

232    activity (measured as the probability of a bat pass per unit area) in the first distance bands (*P.*

233    *pipistrellus* (Figure 1a): 0.057; *P. pygmaeus* (Figure 1b): 0.109) falls outside the 95% quantiles

234    of point estimates for all other distance bands (combined 95% quantiles for bands 2-5, *P.*

235    *pipistrellus*: 0.062-0.248; *P. pygmaeus*: 0.113-0.399), whereas the means of the distance bands 2-

236    5 all fall within each other's 95% quantiles. There is no such difference for single SWT sites: the

237    predicted means in all distance bands fall within each other's 95% quantiles, although in the case

238  of *P. pipistrellus* activity tends to be lower in the first distance band as well (Figure 1a, single

239  SWT).

240

241  **DISCUSSION**

242  We show that, when accounting for confounding effects of habitat and environmental conditions,

243  activity of *P. pipistrellus* activity is lower at 0-100m from installed SWTs, compared to 200-

244  500m. Although not apparent in estimated model parameters, assessment of predictions suggests

245  that this may also be the case for *P. pygmaeus* activity but this effect was weaker. Similarly, the

246  distribution of model predictions suggest that the negative effect of SWT presence in the

247  "closest" distance band is particularly prominent in sites with multiple SWTs installed, with an

248  apparent absence of any difference between distance bands in the activity of *P. pygmaeus* in

249  single SWT sites.

250  On this basis, we conclude that the adverse effect of SWTs on *Pipistrellus* bat activity shown

251  previously (Minderman *et al.* 2012) may in some cases persist over longer distances in the

252  landscape. Although here we show that differences in average predicted activity may be

253  measured when comparing 0-100m to 200-500m distance bands from SWTs, it should be

254  stressed that this does not show that adverse effects would remain evident at 100m from SWTs.

255  Indeed, our previous study (Minderman *et al.* 2012) showed a potential drop in average activity

256  of up to 50% within 25m from operating SWTs. Even in the absence of strong effects beyond

257  25m, this alone could explain the difference between 0-100m and 200-500m shown in the

258  current study. Nevertheless, the present findings do suggest that *Pipistrellus* bats may avoid

259  SWTs on a wider (landscape) scale than previously demonstrated.

260   Although the mechanism for any avoidance behaviour is unclear, experimental studies in a

261   laboratory setting have shown that the return of echolocation pulses off spinning turbine blades

262   may be erratic, potentially causing navigational problems for bats (Long, Flint & Lepper 2010).

263   Alternatively, some bats may avoid foraging in noisy environments (Schaub, Ostwald & Siemers

264   2008) but whether noise generated by turbines (including SWTs) has this effect has not been

265   tested. In either case, it would be reasonable to assume that the strength of such interference

266   would dissipate with distance, especially if it involves high-frequency noise (which attenuates

267   quickly over distance), limiting the spatial scale of any adverse effect of the turbine. However,

268   neither the extent of acoustic noise generated by SWTs nor how this operates over any distance

269   has been studied, so it is unclear to what extent this could explain the results show here.

270   Furthermore, although the model parameter estimates provide no evidence that such avoidance is

271   stronger in sites with multiple SWTs installed for either species, model predictions of activity

272   suggest that the decrease in activity in the "near" distance bands tends to be stronger in multiple

273   SWT sites, particularly for *P. pygmaeus* activity (Figure 1b). Given known local avoidance of

274   individual turbines (e.g. Minderman et al. 2012), it is possible that clusters of SWTs installed in

275   relatively close proximity (in our sample between 12 and 90m apart with mean 46.4m and only

276   one site >62m and <25m respectively) to each other have adverse effects over longer distances.

277   For example, while local avoidance of single turbines may cause local changes of commuting

278   routes, multiple SWTs may cause the loss of such routes altogether (similar to the effect of

279   lighting on bat activity; Stone *et al.* 2009). However, given the mixed evidence for the interactive

280   effect between number of turbines and proximity in the current study, this suggestion needs

281   further study. Moreover, the possibility of cumulative effects (i.e. the combined effect of

282   multiple wind farm sites in a wider area, "regionally cumulative effects") is often raised for

283 larger turbines and wind farms (Masden *et al.* 2010; SNH 2012). Here we aimed to answer a

284 slightly different question, namely whether the installation of a larger number of SWTs installed

285 in a single site increases the effect on bats (i.e. "locally cumulative effects"). The findings

286 reported here should thus not be used to draw conclusions on whether the effects of multiple

287 SWT sites developed in a wider area could combine into a "regional cumulative effect". Finally,

288 it should be stressed that in accordance with our previous findings (Minderman et al. 2012) we

289 do not find any evidence for the hypothesis that the species studied here are attracted to small

290 wind turbines, as suggested for other species by Cryan *et al.* (2014). The suggestion that the

291 interactive effect between SWT proximity and the number of SWTs installed is stronger for *P.*

292 *pygmaeus* activity is in itself interesting, as it highlights the possibility that different species vary

293 in their response to SWT presence. Although morphologically similar, the two species

294 considered here are different in a number of key ecological aspects, including habitat preferences

295 (Vaughan 1997, Nicholls and Racey 2006, Lintott et al 2015). Although our own findings reflect

296 this (e.g. strong positive effects of proportion of woodland on *P. pygmaeus*, but not *P.*

297 *pipistrellus*), whether such ecological differences between these species affect their response to

298 SWT presence remains to be tested, and unfortunately we did not have sufficient statistical

299 power to do so here.

300 There are a number of important caveats with our findings. First of all, these data should not be

301 generalized to species other than *Pipistrellus* spp. Although *Pipistrellus* bats are by far the

302 commonest species in both our wider study area as well as in the specific habitats we studied

303 (Middleton 2006), it is likely that the collection of sufficient data to draw further species-specific

304 conclusions would require targeted surveys. The need to collect data at a wide range of sites

305 prevented us from doing this here. However, the effect of larger turbines in wind farms can vary

306 between species (e.g. collision mortality can vary between species depending on environmental

307 conditions, Baerwald & Barclay 2011) and we therefore consider this to be a research priority for

308 SWTs. Secondly, the limited number of sites with more than two turbines in our sample means

309 that we cannot exclude the possibility that a larger number of turbines would cause stronger

310 effects; indeed modelling studies in birds (Schaub 2012) suggest that this may well be the case.

311 However, based on our own experience and anecdotal data collected during the construction of

312 our SWT owner database (e.g. Park, Turner & Minderman 2013), we feel that our sample of sites

313 fairly represents the usual number of SWTs installed per site; sites with more than two and in

314 particular more than three SWTs remain relatively rare in the UK. Finally, the combination of

315 recording bat activity over a relatively large scale (up to 500m from SWTs) along transects, and

316 a distance-based approach to turbine effects, required that we analysed our data in distance

317 bands. As noted previously, our choice of relatively 'coarse' 100m distance bands may limit our

318 ability to draw conclusions on the exact distance over which avoidance behaviour might operate,

319 but small scale effects have already been studied (Minderman et al. 2012) and we here chose to

320 focus on wider-scale effects. In addition, to allow us to generalise our sampling regime across

321 sites with single and multiple SWTs, we chose to use single starting locations for all transects.

322 As a result, in some cases where multiple SWTs were present, this may have caused some

323 imprecision in the allocation of individual passes to distance bands (as exact distance to

324 individual turbines would differ by a small amount). However, our choice of transect placement

325 minimised any such possible bias: in multiple SWT sites, transects were oriented in such a way

326 that they were as close to perpendicular to the orientation of the SWT "line". In cases where this

327 was impossible, e.g. one of the transects would pass within 50m of another turbine, the transect

328 in question was excluded from the analyses presented here (i.e. leading to some sites with <4

329    transects, see Methods). Moreover, accurately allocating bat passes to even more narrow distance

330    bands is likely to introduce false precision. Thus, collecting data on behavioural responses to

331    turbines on a finer scale would require alternative methods.

332    In conclusion, we suggest that adverse effects of SWTs on *Pipistrellus* bat activity may be

333    measurable over a greater spatial scale than previously thought (0-100m), although combined

334    with our previous work it is likely that much of such avoidance behaviour occurs in relatively

335    close proximity to turbines (<25m). It appears that such effects are stronger when multiple SWTs

336    are installed, particularly for *P. pygmaeus*, but this requires further study. Finally, it should be

337    stressed that the effects reported here are on bat activity only. Although they may reflect changes

338    in habitat use, and this may in turn lead to population-level effects, direct effects of SWT

339    developments on the latter remain to be studied and the conclusions drawn here cannot be thus

340    extrapolated.

341    The SWT sector is expanding rapidly worldwide, and as a result planners and decision makers

342    are increasingly faced with having to advise or decide on planned developments of multiple

343    SWTs in clusters. To date, there were no data to inform such decisions, and the findings

344    presented here are therefore vital and timely. We reiterate our recommendation that individual

345    SWTs within the range of sizes considered here (6-25m hub height) should be sited away from

346    potentially valuable bat habitat (at least >25m, Minderman *et al.* 2012), but based on the current

347    findings we further stress that particular care should be taken in landscapes where limited

348    alternative habitats are available. This would include known roost, commuting and foraging

349    sites. In addition, on the basis of the potential for wider landscape scale effects on some species,

350    we suggest that the (at least the potential for) presence of particularly vulnerable or locally rare

351     species is assessed within 100m from proposed sites, particularly when more than one turbine is

352     planned.

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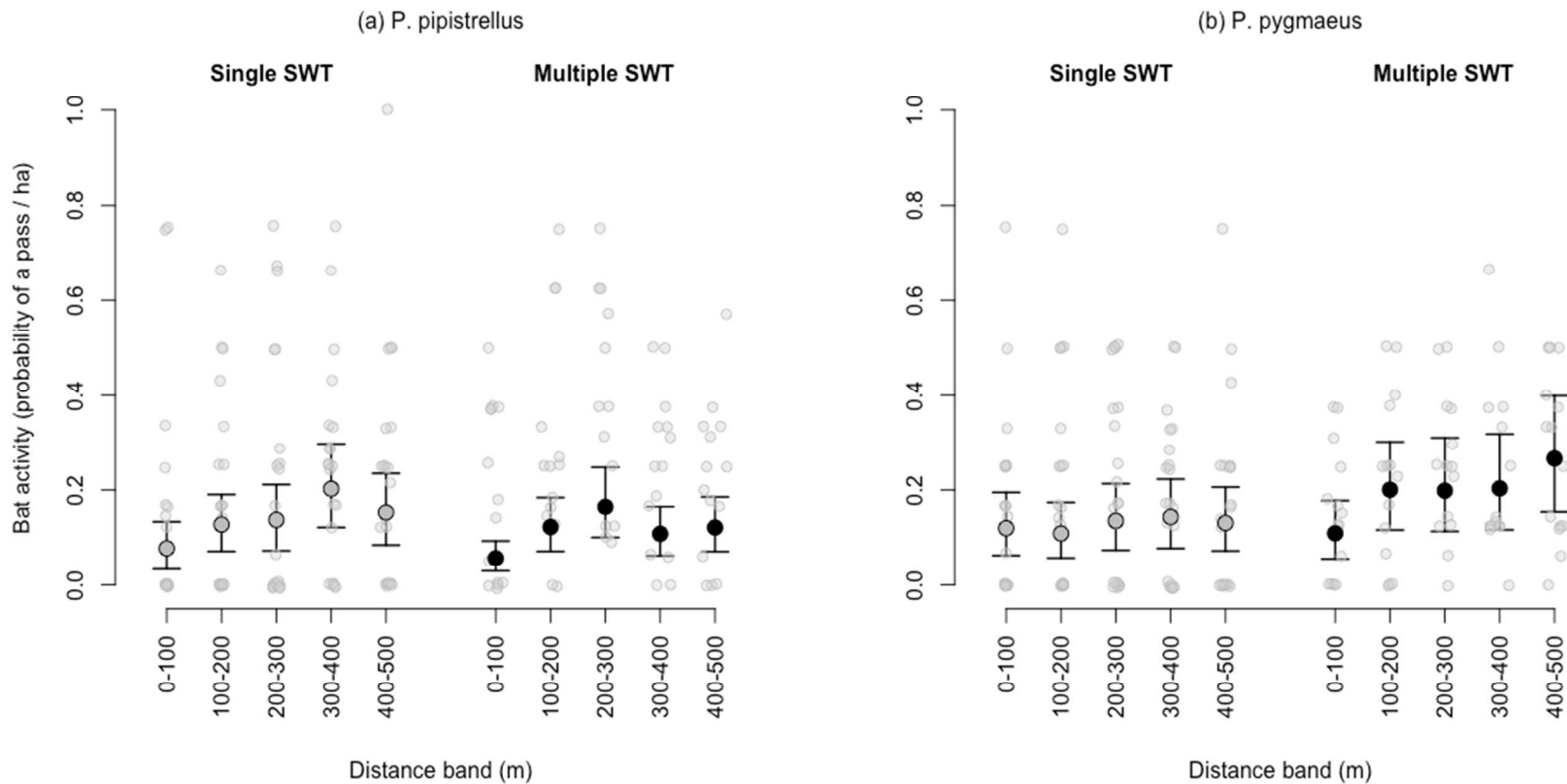
437 **Table 1.** Parameter estimates (*b*) and their standard errors (S.E.) from Generalized Linear Mixed

438 Effects Models (GLMMs) for the activity (probability of a pass ha$^{-1}$) of **(a)** *P. Pipistrellus* and

439 **(b)** *P. pygmaeus*. All models included site and transect within site as a nested random effect

440 structure (variance estimates at the bottom of the table), had binomial errors and were fitted with

441 a complimentary log-log link. All coefficients are parameter estimates based on model fits using

442 standardised (centered and scaled to 1 SD) inputs. Instances where the point estimate ± 2*S.E.

443 does not overlap zero are highlighted in bold, indicating evidence that the parameter is different

444 from zero.

| Fixed effects | (a) *P. pipistrellus* | | | (b) *P. pygmaeus* | |
|---|---|---|---|---|---|
| | *b* | S.E. | | *b* | S.E. |
| (Intercept) | **-2.203** | **0.197** | | **-1.864** | **0.198** |
| Distance band 2 (100-200m) | **0.521** | **0.208** | | 0.174 | 0.203 |
| Distance band 3 (200-300m) | **0.730** | **0.207** | | 0.253 | 0.205 |
| Distance band 4 (300-400m) | **0.596** | **0.213** | | 0.232 | 0.210 |
| Distance band 5 (400-500m) | **0.489** | **0.223** | | 0.306 | 0.211 |
| No. turbines (multiple) | -0.080 | 0.367 | | -0.263 | 0.363 |
| Min 24h. Temperature | -0.041 | 0.150 | | -0.099 | 0.162 |
| Day number | 0.124 | 0.203 | | **0.739** | **0.195** |
| Year (2014) | **0.826** | **0.252** | | -0.602 | 0.301 |
| Time to midnight | **-0.536** | **0.156** | | 0.294 | 0.175 |
| Time to midnight$^2$ | -0.472 | 0.287 | | **-1.208** | **0.332** |
| Wind speed (m s$^{-1}$) | **-0.549** | **0.172** | | **-0.759** | **0.191** |
| Edge density (m m$^{-2}$) | **0.670** | **0.132** | | **0.620** | **0.144** |
| Proportion woodland | -0.067 | 0.141 | | **0.493** | **0.125** |
| D. band 2 * no. turbines | 0.260 | 0.428 | | 0.693 | 0.412 |
| D. band 3 * no. turbines | 0.433 | 0.422 | | 0.421 | 0.405 |
| D. band 4 * no. turbines | -0.379 | 0.424 | | 0.461 | 0.411 |
| D. band 5 * no. turbines | -0.018 | 0.443 | | 0.781 | 0.412 |
| *Random effects σ$^2$* | | | | | |
| Transect / Site | 0.374 | | | 0.579 | |
| Site | 0.377 | | | 0.447 | |
| *Model fit* | | | | | |
| Marginal *R$^2$* | 0.304 | | | 0.255 | |
| Conditional *R$^2$* | 0.451 | | | 0.507 | |

445 **FIGURE CAPTIONS**

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446    **Figure 1**. Observed (small grey points, average per site visit) and predicted (dark grey and black

447    points, and lines) of **(a)** *P. pipistrellus*, and **(b)** *P. pygmaeus* activity (probability of a pass ha$^{-1}$)

448    in five distance bands from single- and multiple SWT installations. Predictions are based on

449    model fits using standardized (scaled and centered) bat activity from Generalized Linear Mixed

450    Effects Models (GLMMs, Table 1), in each of five distance bands around small wind turbines.

451    Dark grey circles and their corresponding lines are predicted median levels for single-turbine

452    sites, and black circles and their corresponding lines are median levels for multiple-turbine sites.

453    Small grey dots are the observed mean probabilities of obtaining a bat pass across all

454    observations in each distance class, for each site. The error bars (lines) are the 95% quantiles of

455    predictions calculated from N = 1000 bootstrap samples of estimated parameter distributions.

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457  **Figure 1.**

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1  **Landscape-scale effects of single- and multiple small wind turbines on bat activity**

2  *Jeroen Minderman, Mairi H. Gillis, Helen F. Daly & Kirsty J. Park*

3

4  **Supplementary material**

5

6  **Preliminary habitat data analysis and additional tables**

7  A total of 10 habitat variables were quantified in each transect section in all sites (Table A2),

8  using 1:1250 UK Ordnance Survey MasterMap Topography digital map (OS) data and QGIS v.

9  1.8. These variables were chosen on the basis of their known potential effect on bat activity. The

10  five proportion land cover variables (proportion buildings, road or tracks, rough grassland,

11  roadside, and woodland) were calculated from the OS polygon area data and were calculated as

12  the sum of each of these five land cover types in each transect section, divided by the size of the

13  transect section. These were defined as the total area size of all polygons listed as (1) "Buildings"

14  in the *Theme* field; (2) "Road Tracks and Paths" in the *Theme* field; (3) "Rough grassland"

15  (including all lower classifications) in the *descrTerm* field; (4) "Roadside" in the *descrGroup*

16  field and (5) "Coniferous or Nonconiferous trees"" in the *descrGroup* field. The four distance

17  variables (distance to buildings, linear features, trees and water) were calculated by overlaying

18  the OS data with a 1x1m 'raster' of grid cells, calculating the distance (m) between each raster

19  cell and the nearest raster cell containing each of the four land cover types (respectively,

20  buildings as defined above, any linear feature as contained in the OS "line" data, any woodland

21  as defined above and any water polygon), and averaging these distances for all cells within the

22  transect sections.

23    Finally, edge density (m m$^{-2}$) was expressed as the total length of all line features contained in

24    the OS Linear data per transect section, divided by the transect section area. Line features

25    include e.g. building-, woodland and water edges, hedgerows, roads and tracks, roadsides, and

26    field boundaries.

27    To identify a subset of habitat variables that were most descriptive of bat activity (see main text),

28    we ran an initial model selection procedure on a Generalized Linear Mixed Effects (GLMM)

29    model for the probability of a bat pass per hectare as a function of all 10 habitat variables only.

30    In addition to these habitat variables this model included transect within site as a random effect,

31    a binomial error distribution with a log-log link function and transect section size (ha) as an

32    offset. To avoid problems with collinearity, we limited the full model set to include only one of

33    the five 'proportion' habitat variables (because these represent proportion cover, lower cover of

34    one automatically implies greater cover of another, leading to high collinearity). We further

35    excluded all models including (1) **both** proportion of woodland and distance to trees, (2) **both**

36    proportion buildings and distance to buildings, (3) **both** edge density and distance to linear

37    features **or** proportion of roads or tracks. Again, these latter exclusions were to avoid high

38    collinearity. For example, a greater proportion of woodland in a given transect section naturally

39    implies shorter distances to trees; edge density includes linear features such roads and tracks; etc.

40    Thus, these variables effectively measured very similar things but in slightly different ways. All

41    model fitting procedures and analyses followed the methodology described in the main text.

42    The resulting full model set comprised of a total of 112 models. The candidate set (ΔAICc<4)

43    contained 4 models. The 'top' model retained three of the ten habitat variables: distance to water,

44    edge density and the proportion of woodland (Table A3). Distance to water was only included in

45    two out of the four models in the top set, however. By contrast, edge density and the proportion

46    of woodland were retained in all four models in the candidate set. Thus, we chose to use edge

47    density and the proportion of woodland as the key two habitat variables explaining bat activity.

48    As discussed, we chose to limit the number of explanatory variables for the models for bat

49    activity in this way to avoid problems with overparameterisation. However, we did test whether

50    the inclusion of distance to water (because of the known importance of riparian habitats to *P.*

51    *pygmaeus* in particular) made any difference to the models presented in Table 1 in the main text

52    or whether it would change their interpretation. The estimated effect of distance to water was not

53    significantly different from zero in either the model for *P. pipistrellus* (-0.259 +/- 0.151) or the

54    model for *P. pygmaeus* (-0.043 +/- 0.181, although convergence of the estimates of this model

55    was poor, presumably due to overparameterisation), neither was the interpretation or significance

56    of any of the other parameters changed by its inclusions.

57    Similarly, we tested whether the inclusion of turbine hub height as an extra predictor, as well as

58    its interaction with distance from turbines, affected our results. As per the addition of distance to

59    water, this did lead to estimation problems for some of the models under consideration. Bearing

60    this in mind, none of the interaction terms between hub height and distance from turbine were

61    different from zero for either the *P. pipistrellus* or *P. pygmaeus* models, and when this

62    interaction term was further dropped from both models, the effect of hub height was not different

63    from zero in either model (*P. pipistrellus*: -0.119 +/- 0.231; *P. pygmaeus*: -0.124 +/- 0.268). The

64    remaining parameter estimates and their interpretation also remain qualitatively unchanged.

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68    **Table A1**. Descriptive statistics of predictor variables in the Generalized Linear Mixed Model

69    (GLMM) for *Pipistrellus* sp. bat activity (Table 1), on their original (unstandardised) scale.

|  | Mean | Median | Std. dev | Min. | Max. |
|---|---|---|---|---|---|
| **Minimum 24h temperature (°C)** | 11.76 | 12.00 | 2.75 | 5.00 | 17.60 |
| **Julian day number** | 196.59 | 195.00 | 28.85 | 147.00 | 246.00 |
| **Time to midnight (min)** | -26.07 | -41.00 | 82.54 | -202.30 | 197.77 |
| **Time to midnight$^2$** | 7487.47 | 4669.44 | 8375.13 | 0.00 | 40925.29 |
| **Wind speed (m s$^{-1}$)** | 1.07 | 0.40 | 1.46 | 0.00 | 9.80 |
| **Edge density (m m$^{-2}$)** | 0.04 | 0.03 | 0.02 | 0.00 | 0.13 |
| **Proportion woodland** | 0.05 | 0.00 | 0.13 | 0.00 | 0.92 |

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71    **Table A2.** Descriptive statistics of all ten original habitat variables as predictors for bat activity on their original (unstandardised)

72    scale, split by single- and multiple SWT sites.

73

| | Single turbines | | | | | Multiple turbines (2-4) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **Median** | **SD** | **Min.** | **Max.** | **Mean** | **Median** | **SD** | **Min.** | **Max.** |
| Distance to buildings (m) | 174.48 | 152.02 | 114.83 | 13.65 | 596.93 | 222.76 | 209.89 | 135.88 | 9.2 | 623.77 |
| Distance to linear features (m) | 24.67 | 17.92 | 21.86 | 5.9 | 132.37 | 21.09 | 18.5 | 16.5 | 5.37 | 190.97 |
| Distance to trees (m) | 144.88 | 125.65 | 110.28 | 0.19 | 519.74 | 211.45 | 196.33 | 150.86 | 1.89 | 646.47 |
| Distance to water (m) | 218.3 | 174 | 166.43 | 13.2 | 689.27 | 186.47 | 153.42 | 142.33 | 17.88 | 652.74 |
| Edge density (m m$^{-2}$) | 0.04 | 0.03 | 0.03 | 0.00 | 0.13 | 0.04 | 0.04 | 0.02 | 0.00 | 0.13 |
| Proportion of buildings | 0.01 | 0.00 | 0.03 | 0.00 | 0.20 | 0.01 | 0.00 | 0.04 | 0.00 | 0.29 |
| Proportion of roads or tracks | 0.02 | 0.01 | 0.03 | 0.00 | 0.26 | 0.02 | 0.01 | 0.03 | 0.00 | 0.15 |
| Proportion of rough grassland | 0.07 | 0.00 | 0.18 | 0.00 | 1.00 | 0.02 | 0.00 | 0.07 | 0.00 | 0.49 |
| Proportion of roadsides | 0.02 | 0.00 | 0.04 | 0.00 | 0.26 | 0.02 | 0.00 | 0.03 | 0.00 | 0.14 |
| Proportion of woodland | 0.07 | 0.00 | 0.15 | 0.00 | 0.92 | 0.04 | 0.00 | 0.12 | 0.00 | 0.77 |

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74 **Table A3.** Candidate set of Generalized Linear Mixed Models for bat activity (probability of bat

75 activity ha$^{-1}$, binomial errors, complementary log-log link) within 4 AICc points of the "top"

76 model, as a function of ten candidate habitat predictors only. Coefficients are parameter

77 estimates based on models fit using standardized (centered and scaled to 1 SD) inputs. K is the

78 number of parameters in the models. All models included site and transect within site as a nested

79 random effect structure.

| Model | Intercept | Distance to buildings | Distance to water | Edge density | Proportion woodland | K | Log-likelihood | AICc | Δ AICc | Model weight |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1.146 | | -0.305 | 0.523 | 0.41 | 6 | -824.8 | 1661.7 | 0.000 | 0.541 |
| 2 | -1.146 | 0.028 | -0.301 | 0.532 | 0.408 | 7 | -824.8 | 1663.7 | 1.962 | 0.203 |
| 3 | -1.139 | | | 0.549 | 0.445 | 5 | -826.9 | 1663.9 | 2.184 | 0.181 |
| 4 | -1.138 | 0.059 | | 0.568 | 0.438 | 6 | -826.8 | 1665.7 | 3.957 | 0.075 |

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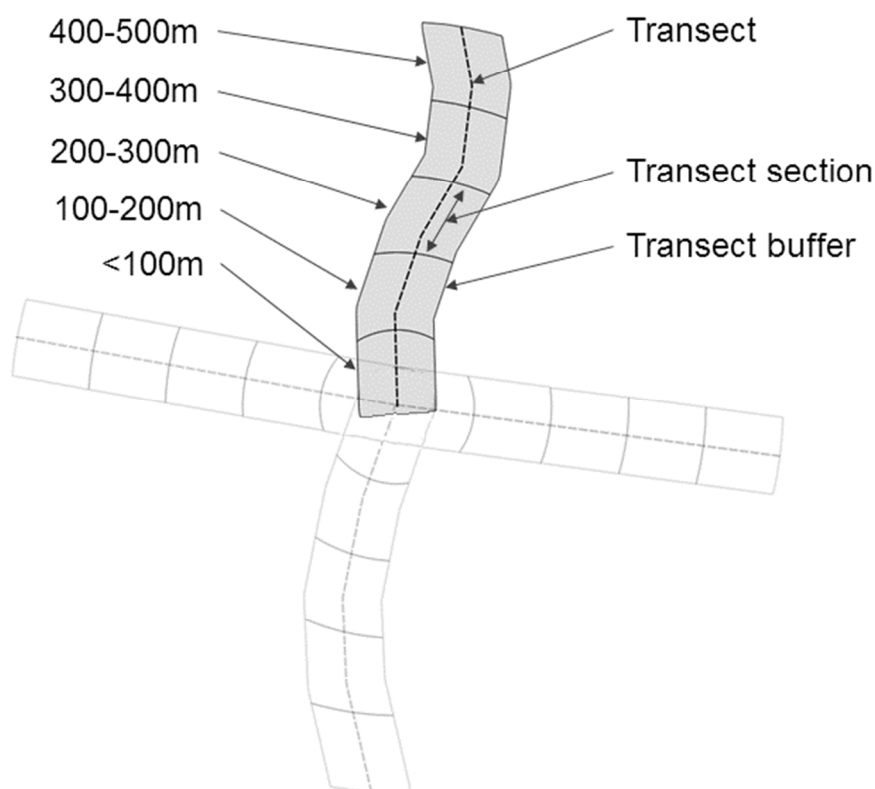
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83    **Figure A1**. Conceptual example of a bat transect layout. The turbine is at the intersection of the

84    transects. The dashed lines show the transects walked, whereas the solid line represents the area

85    for which The habitat surrounding the turbines varied significantly between sites, and this was

86    reflected in transect placement, so that (1) the combination of all transects within each site

87    covered all major habitats present, and (2) overall distance separating each transect was

88    maximized.

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