

Ecography

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Supplementary material

1 **APPENDIX**

2 **Details of the behavioral responses of migrants in relation to atmospheric conditions and geographic**
3 **features**

4

5 **1. Flight initiation, termination and migration intensity**

6 *Insects*

7 WIND: Radar studies have revealed that wind speed and direction have pronounced effects on
8 migratory departure and landing and consequently on the intensity of migration aloft (Rose et al. 1985,
9 Chapman et al. 2010, 2015a, Drake and Reynolds 2012). Favorable seasonal tailwinds (e.g. northerlies in
10 autumn) are associated with high migration intensity of many insects over the southern UK (Hu et al.
11 2016). Specifically, seasonally advantageous high-altitude tailwinds promote the initiation and
12 maintenance of migratory flight of autumn generation of the noctuid moth *Autographa gamma* heading
13 south, from northern Europe to the wintering grounds around the Mediterranean Sea (Chapman et al. 2008,
14 2015b). Airflows associated with synoptic scale fronts can provide short term ‘windows’ for crucial,
15 seasonally-adaptive movements in directions different from those in which the prevailing wind direction
16 would take the migrants. For example, massive autumn insect migration was associated with the passage
17 of synoptic-scale cold fronts, with insects flying in northerly winds immediately behind the leading edge
18 of the front (e.g., Beerwinkle et al. 1994, Feng et al. 2009, Chapman et al. 2010). Drake et al. (1981)
19 recorded spring movements of moths from the Australian mainland into Tasmania on warm northerly
20 (anticyclonic) airflows *ahead* of an approaching cold front. These rapid seasonal migrations may account
21 for large fluxes of insect biomass (Hu et al. 2016). Additionally, insects are often caught in the outflow
22 boundaries of convective storms (e.g., Achtemeier 1991, Browning et al. 2011) that may disperse insects
23 over long distances (e.g. Wilson and Schreiber 1986) and may also be trapped in the ‘eye’ or the rear of
24 hurricanes and typhoons (Van den Broeke 2013, Ma et al. 2018).

25 PRECIPITATION, CLOUDS AND FOG: Responses to, and effects of, rain on insect migration
26 are complex (Drake and Reynolds 2012, Reynolds et al. 2018). In temperate areas, rainy weather may

27 inhibit insect flight because of the associated lower air temperatures (and/or the cessation of convection in
28 the case of small day-flying insects, Russell 1999), and heavy, widespread rainfall inhibits insect flight
29 initiation and induces its termination (Drake and Reynolds 2012, but see Drake et al. 1981). Interestingly,
30 a sudden increase in nocturnal dragonfly migration over the Bohai Sea in northern China coincided with
31 foggy weather (Feng et al. 2006). Probably the flight of this diurnal migrant *Pantala flavescens* were
32 extended after dark because the insects found themselves over the sea, and the foggy conditions commonly
33 associated with the migration events might have also interfered with visual detection of ground features
34 (e.g. the coastline), which might otherwise have promoted landing (Feng et al. 2006). This could be because
35 fog is usually associated with relatively calm conditions at the surface, as indeed found in these heavy-
36 migration nights. The migrants were probably flying above the fog and likely departed for their journey at
37 dusk before the fog formed.

38 TEMPERATURE AND THERMAL UPDRAFTS: Because insects are poikilotherms, temperature
39 requirements for take-off and maintenance of flight must be satisfied first (Chapter 9 in Drake and
40 Reynolds 2012). Consequently, insects usually have a threshold temperature below which flight cannot be
41 initiated and/or maintained (e.g., Dudley 2000, Drake and Reynolds 2012). Temperature thresholds are
42 highly variable depending on the species, but various radar studies report that insects are usually detected
43 only when surface temperatures exceed 10°C (Wilson et al. 1994, Chapter 15 in Drake and Reynolds 2012),
44 likely representing an approximate threshold temperature for flight initiation in insects. In autumn, falling
45 temperatures promote the initiation of migratory flights in red admiral butterfly (Mikkola 2003), thus
46 increasing the probability of windborne transport on cool northerlies. Although some butterflies use soaring
47 flight (e.g., Gibo and Pallett 1979), we are not aware of any radar studies that explored it.

48 TOPOGRAPHY: To the best of our knowledge there are no radar studies on direct effects of
49 topography on flight initiation and/or termination of insect migration, largely because insect echoes on
50 scanning radars at low altitudes are swamped by much stronger ‘clutter’ echoes from ground features in
51 mountainous areas. However, entomological vertical-looking or tracking radars are generally less affected

52 by ground clutter and may thus be applied in the future to address questions related to the effects of
53 topography on migratory departure and termination.

54 WATER-LAND INTERFACE: Usually, nocturnal insect migration is largely halted by the onset
55 of dawn (Drake and Reynolds 2012). Yet, this termination of migratory movement is overridden if insect
56 migrants find themselves over water. Accordingly, the range of insect movement under these
57 circumstances may be considerably extended (Drake et al. 1981, Feng et al. 2009).

58 HUMAN AND INFRASTRUCTURE DEVELOPMENT: There are some incidental radar
59 observations of concentrations of insects around lights of large towns (e.g. Wad Madani in Sudan, see p.
60 275 in Drake and Reynolds 2012) and additional studies reported the attraction of large numbers of radar-
61 observed insect migrants to light traps following their descent from an overflying layer concentration and
62 subsequent flight near the ground near the trap (Reynolds and Riley 1988, Drake and Reynolds 2012, see
63 also Muirhead-Thompson 1991).

64

65 *Birds*

66 WIND: There is a balance between several endogenous and exogenous factors making up a bird's
67 decision to take off, and these include the bird's body condition, the quality of the resting site and the
68 meteorological conditions. Radar data showed that birds migrating selectively during nights with favorable
69 wind conditions speed up their flight by 30% (on average) compared to those disregarding the wind (Liechti
70 and Bruderer 1998), with likely implications for energy conservation (Pennycuick 1978, Alerstam 1991).
71 Several radar studies reported that flapping birds, such as waders, woodpigeons, starlings and geese, select
72 tailwinds to initiate their migration (e.g. Richardson and Haight 1970, Alerstam and and Ulfstrand 1974,
73 Green 2004). Migrating geese are selective in their choice of migration days and waders were found to
74 migrate in days with strong tailwinds that may even exceed the birds' own airspeeds (Green 2004).

75 Synoptic patterns of bird migration are structured by the presence of cyclones and anticyclones at
76 temperate latitudes, both in horizontal and altitudinal dimensions (Richardson 1978a, 1990). Early radar
77 studies in North America (Nisbet and Drury 1968, Richardson and Haight 1970, Richardson 1971,

78 Richardson and Gunn 1971) and Switzerland (Bruderer 1971) indicated that substantial spring migrations
79 initiate and continue under the light variable winds and fair weather that are typical near the centers of
80 high-pressure areas and in southerlies (spring migration tailwinds). Strong autumn migration occurs in the
81 eastern and central parts of high-pressure areas shortly after the passage of cold fronts in North America
82 (Richardson and Gunn 1971, Able 1972, Richardson 1972), Europe (Williamson 1969, Alerstam et al.
83 1973, Nilsson et al. 2019) and China (Mao 1985, Williams 1986), in light winds and strong northerlies
84 (autumn migration tailwinds).

85 In some cases, departure decisions could be fatal. Historical data from weather radar and water-
86 and land-based weather stations enabled Diehl et al. (2014) to reconstruct the circumstances leading to
87 mass bird mortality documented along the shores of Lake Michigan in northeastern Illinois in May 1996.
88 Storms that included strong winds, as well as heavy rain and hail, pushed birds over the lake and led to the
89 documented death of almost 3000 migratory birds from 114 species, mostly small passerines whose
90 carcasses were found in the lake's shores, with the actual numbers of dead birds likely much higher.

91 PRECIPITATION, CLOUDS AND FOG: Rain and precipitation, in general, are known to
92 suppress migratory flight (Richardson 1978a, 1990), but one must note that radars are unable to detect
93 birds that are flying under heavy rain. Also, fog may affect migration timing because migrating birds may
94 postpone their departure when visibility is poor (Alerstam 1990, Richardson 1990, Panuccio et al. 2019).

95 TEMPERATURE AND THERMAL UPDRAFTS: There is a strong relationship between rising
96 temperature and high migration intensity in spring (dropping temperature in autumn), as well as the
97 likelihood of flight initiation (Richardson 1978a, 1990). Temperature is the most important predictor of
98 spring migration timing and intensity based on data from a weather radar network deployed across North
99 America (Van Doren and Horton 2018). The same study also discriminated the effects of wind and
100 temperature: in similar wind conditions, more birds took flight when temperatures were warmer. Soaring
101 birds exploit thermal updrafts forming in the boundary layer during the day and initiate their flight when
102 thermals start developing, after dawn. Conversely, their flight terminates when no strong thermal are
103 available, after sunset (Spaar and Bruderer 1996, 1997).

104 TOPOGRAPHY: Radar studies have so far not found effects of mountain barriers on initiation or
105 termination of bird migration. Generally, birds tend to avoid high terrain elevations, as migration intensities
106 over mountains are substantially lower (sometimes by as much as 90%) compared to those over lowlands
107 (the Alps: Bruderer 1978, Liechti et al. 1996b, Aurbach et al. 2018; the Appalachians: Williams et al. 2001;
108 the Galilee in Northern Israel: Liechti et al. 2019). This ‘funneling effect’ described by higher bird
109 migration densities within the lowlands compared to low migration intensities over mountains, shows that
110 local topography may strongly influence migration patterns and can lead to local concentration of migrants
111 (Bruderer and Liechti 1990, Liechti et al. 1996b).

112 WATER-LAND INTERFACE: Land birds likely decide whether to stop, follow the coast or cross
113 the sea by considering the possible fatal consequences of drifting over the sea (Alerstam and Pettersson
114 1977, Horton et al. 2016). Bird decisions are related to the geographic settings (e.g., the width of the
115 crossing and coastline direction in relation to goal direction), as well as the specific wind conditions at the
116 crossing point. Several radar studies found no, or only weak, coastline effects on landing decision during
117 autumn and spring migration (Bruderer and Liechti 1998, Zehnder et al. 2001, Nilsson et al. 2014). One
118 explanation could be a progressive change of flight heading throughout the night, with an increasing rate
119 of migration towards land during the second part of the night, presumably due to the birds’ preference to
120 stop-over and cease cross-country flight during the day (Alfia 1995, Bruderer and Liechti 1998, Horton et
121 al. 2016; see also Diehl et al. 2003). Radar observations have revealed that the peak longitude of arrival at
122 the coast for birds migrating aloft is related to the annual variability in the average wind speed and direction
123 over the Gulf of Mexico (Gauthreaux et al. 2006). Moreover, the average wind speed and direction over
124 the Gulf of Mexico affected also longitudinal patterns in the distribution of birds leaving stopover sites
125 along the coast during spring (Lafleur et al. 2016). Furthermore, nocturnally-migrating birds that were
126 found over the Great Lakes of North America at dawn were observed to gain altitude until seeing the closest
127 shoreline in their vicinity to which they reoriented rather than continued their cross-water journeys, leading
128 to greater densities of birds stopping-over near the shore (Archibald et al. 2017).

129 HUMAN AND INFRASTRUCTURE DEVELOPMENT: Although artificial light at night
130 associated with human development has been known to influence migrating birds during flight for
131 hundreds of years (Gauthreaux and Belser 2006), the response of birds to artificial light when initiating or
132 terminating migratory flight is not well understood. Recent weather radar studies have revealed that
133 migrating land birds stop-over in relatively high densities in city parks (Buler and Dawson 2014) and nearer
134 to highly light-polluted areas (McLaren et al. 2018). This broad extent stopover pattern may be caused by
135 young migrants orienting towards the skyglow of cities (Gauthreaux 1982) while selecting landing sites at
136 the termination of migratory flight. Estimating fine-scale temporal differences in departure timing is
137 possible with weather radar (Buler et al. 2018), revealing the influence of human development on migratory
138 flight initiation at a scale beyond the individual.

139

140 **2. In-flight behavior: speed, direction and altitude**

141 *Insects*

142 WIND: The optimal response of a flapping migrant to tailwinds is airspeed reduction, to decrease
143 the metabolic cost of flight. Higher airspeed is expected in headwind conditions (Pennycuick 1978). The
144 response of insects to wind conditions is strongly constrained by their lower airspeeds (Schaefer 1976,
145 Larkin 1991), which is virtually negligible in small insects. Migrating insects experiencing crosswinds
146 show a variety of responses, including complete and partial drift, as well as complete compensation for
147 lateral displacement in light winds (Chapman et al. 2010, 2015a,b, Reynolds et al. 2016). Preference for a
148 specific altitude was found to relate to strong wind support (Drake 1985, Wood et al. 2006, Drake and
149 Reynolds 2012). For instance, red admiral butterflies *Vanessa atalanta* chose cool northerly tailwinds for
150 their southern migrations from Scandinavia. They furthermore fly at high altitudes when strong winds from
151 the north predominate, but descend lower down when migrating in headwinds (Mikkola 2003).

152 Long-distance insect movements are typical in steady flows caused by the global-scale wind
153 patterns and the synoptic weather systems embedded within them, for example, the depressions and
154 anticyclones within the mid-latitude westerlies. Synoptic-scale winds (that are usually associated with

155 specific air temperature and precipitation conditions) may facilitate or impede insect migration. For
156 example, the seasonal insect invasions of higher latitudes in spring often occur during spells of warm
157 southerlies (northerlies in the southern hemisphere) on the western flank side of an anticyclone (Drake and
158 Reynolds 2012).

159 PRECIPITATION, CLOUDS AND FOG: In the case of convective rain, insect migration can
160 continue outside the precipitating cumulonimbus cells (Leskinen et al. 2011, Browning et al. 2011, Drake
161 and Reynolds 2012). Browning et al. (2011) found that insects entrained in layers of warm air flowing into
162 a thunderstorm took no action until they were within a 10-min period before the arrival of the storm's
163 precipitation. They then descended with a tumbling motion – presumably an 'emergency' reaction to avoid
164 being taken up to great altitude (and killed) in the violent updrafts associated with the storm. On several
165 occasions, during nocturnal migration over the Bass Strait in Australia, flying moths were seen to be
166 unaffected by the passage of a rain shower, suggesting that rain do not have any significant effect on their
167 migration, at least if the insects are already airborne when the rain arrives, and the rain is not very heavy
168 (Drake et al. 1981). Heavy, widespread rainfall induces descent that may result in landing and the
169 termination of migration (Drake and Reynolds 2012; see also above).

170 TEMPERATURE AND THERMAL UPDRAFTS: Unlike the effects of temperature on flight
171 initiation (see above Section 1.), radar evidence suggests that, once aloft, some large insects may fly in
172 surprisingly low air temperatures (~5° C) (e.g. Drake and Reynolds 2012), presumably because they
173 generate enough internal heat through their wing-beating action. Interestingly, dragonflies, butterflies and
174 locusts concentrate in the boundaries of convective thermal cells (Schaefer 1976, Drake and Reynolds
175 2012), thus exhibiting a surprisingly convergent flight behavior with that of large soaring birds (Box 3, but
176 see Geerts and Miao 2005).

177 TOPOGRAPHY: Insects were found to concentrate and respond to lee waves, topographic wind
178 eddies and rotors (Chapter 11 in Drake and Reynolds 2012). Additionally, quasi-stationary convergence
179 lines associated with rotors may provide aerial concentrating mechanisms and lead to high-density
180 outbreaks of, for example, the African armyworm (*Spodoptera exempta*) (Rose et al. 2000). No radar study

181 has documented the seasonal near-ground passage of hordes of insects (such as butterflies and hoverflies,
182 Diptera: Syrphidae) through high mountain passes in the Pyrenees and Alps (e.g. Lack and Lack 1951,
183 Aubert et al. 1976).

184 WATER-LAND INTERFACE: Data from meteorological radars suggest a predisposition of
185 insects to resist being carried over coastlines and over the sea (Russell and Wilson 1996, 2001; see also
186 Chapman et al. 2010, 2015a, as well as Shashar et al. 2005). Nonetheless, radars have documented large-
187 scale insect migrations across the sea (e.g. Drake et al. 1981, Feng et al. 2006, 2009).

188 HUMAN AND INFRASTRUCTURE DEVELOPMENT: Despite the well-known attraction of
189 many insects towards artificial lights (the basis of the light-trap), radar detected insects engaged in steady
190 nocturnal migration at altitude do not appear to be affected by lights on the ground (see p. 276 in Drake
191 and Reynolds 2012). The powerful vertical-beam searchlight trap used in some Chinese radar studies (Feng
192 et al. 2009) constitutes an exception, but lights of this sort would rarely be encountered by migrating
193 insects.

194

195 *Birds*

196 WIND: Radar studies reveal the flight strategies of birds when facing various wind conditions.
197 Like in insects, the optimal expected response of a bird flying in tailwinds is airspeed reduction, and
198 airspeed increase in headwinds (Pennycuick 1978). This expectation has been empirically demonstrated in
199 a number of radar studies involving terrestrial flapping birds (Bloch and Bruderer 1982, Williams et al.
200 1986, Gudmundsson et al. 1992, Hedenström et al. 2002), terrestrial soaring-gliding birds (Spaar and
201 Bruderer 1996, 1997, Malmiga et al. 2014, Becciu et al. 2018) and seabirds employing a range of flight
202 modes (Mateos-Rodríguez and Bruderer 2012), with the exception of flapping auks whose response is
203 probably limited by their high wing loading.

204 Migrating birds in crosswinds demonstrate a wide range of strategies involving complete drift, as
205 well as partial and complete compensation for lateral displacement (Green 2001). A radar study in the
206 Strait of Gibraltar found that flapping seabirds (auks, puffins, gannets and small shearwaters) compensate

207 for wind drift independently of the predominant wind direction, unlike the larger shearwater species that
208 use a dynamic directional response to wind, allowing to be drifted in spring when westerly tailwinds are
209 prevalent and compensating for wind drift in autumn, when both easterly and westerly winds are similarly
210 frequent (Mateos-Rodríguez 2009).

211 To reduce metabolic costs of flight and increase ground speed, flying birds may adjust their flight
212 altitude to better exploit tailwinds along their predominant migratory direction. This has been suggested
213 for broad-front nocturnal migrants over Europe and Israel (Bruderer and Liechti 1995, Dokter et al. 2011),
214 as well as for migrating geese over southern Sweden (Green 2004). Diurnal migrating birds that use
215 flapping flight do not explore the entire air column of potential flight altitudes, but instead follow a rule of
216 climbing if tailwind assistance increases (Mateos-Rodríguez and Liechti 2012, Kemp et al. 2013). On the
217 other hand, nocturnal migrants reach higher altitude taking advantage of vertical wind shear, which arises
218 in particular synoptic situations related to the magnitude and direction of large-scale horizontal temperature
219 gradients (Dokter et al. 2013). Flight altitude in soaring migrants depends mainly on thermal conditions
220 (see below).

221 **PRECIPITATION, CLOUDS AND FOG:** Fog and low clouds limit bird visibility during flight
222 and may disrupt bird orientation (Lack 1962, Alerstam 1990, Richardson 1990). Radar-tracked Sandhill
223 cranes (*Grus canadensis*) showed more circuitous flight on a foggy day than on days with good visibility
224 (Kirsch et al. 2015; see also Pastorino et al. 2017). Precipitation, low clouds and fog have a strong influence
225 on visibility and obstacle avoidance behavior over complex terrain (Emlen and Demong 1978, Rüschi and
226 Bruderer 1981). For instance, when visibility is reduced, flight directions are more dispersed (Emlen and
227 Demong 1978, Liechti 1986, Becciu et al. 2017).

228 **TEMPERATURE AND THERMAL UPDRAFTS:** Birds are much more flexible than insects in
229 terms of timing and altitude of flight and may tolerate a wider temperature range. Nevertheless, radar-
230 based studies found that migrating raptors, as well as other soaring birds, increase their ground speed and
231 flight altitude in the hottest hours of the day – at midday and in the afternoon – probably because of the
232 stronger thermal uplift associated with high temperatures (Spaar and Bruderer 1996, Leshem and Yom-

233 Tov 1998). In fact, for soaring birds, flight altitude depends on the strength of thermal uplifts and on the
234 bird's decision to leave an uplift and start gliding (Pennycuick et al. 1979, Kerlinger et al. 1985, Horvitz
235 et al. 2014).

236 TOPOGRAPHY: Radar studies found that birds adjust their flight path with respect to mountain
237 ranges (Rüsch and Bruderer 1981, Liechti 1986, but see Mabee et al. 2006), suggesting that topographic
238 features constitute serious obstacles that animals have to cope with during migration (Bruderer 1978,
239 Liechti et al. 1995, Liechti et al. 1996a, 1996b). Birds were observed to deviate from their regular flight
240 direction to follow local topography through mountain passes (Williams et al. 2001). Nonetheless,
241 Hilgerloh et al. (1992) suggest that the Pyrenees do not constitute an ecological barrier to avian migrants
242 that commonly cross the ridge and similarly, another radar study found no effect of the Allegheny Front
243 ridgeline on autumn nocturnal migrants in West Virginia, USA (Mabee et al. 2006).

244 Weather conditions, such as wind were found to modulate the tendency of low-flying birds to
245 circumvent mountains instead of crossing them (Williams et al. 2001). For instance, circumvention
246 behavior of a complex and rough terrain is more pronounced under headwind conditions when most birds
247 fly at relatively low altitudes (Liechti 1986). On the other hand, under tailwinds birds are prone to cross
248 the Pyrenees in higher numbers (Lack and Lack 1951). Soaring migrants likely exploit orographic uplifts
249 while travelling along mountain ridges (Panuccio et al. 2016). Increasing migration intensity was observed
250 along the Appalachian Mountains that are orientated similar to the birds' main migration direction (Mabee
251 et al. 2006), likely indicating a funneling effect of the mountains. We note that high resolution wind flow
252 description and simulation of movement over complex terrain could provide deeper understanding of the
253 environmental factors faced by travelling birds (see Aurbach et al. 2018).

254 WATER LAND INTERFACE: Metabolic costs associated with flapping flight scale
255 disproportionately high in relation to body mass (Hedenström 1993). Since flapping is the flight mode used
256 by sea-crossing migrants including those which usually soar during flight, a negative relationship between
257 bird size and its sea crossing propensity has been documented in several radar studies. While small raptors
258 routinely cross the sea using flapping flight, likely because of their relatively low flapping flight metabolic

259 costs, larger soaring birds avoid sea crossing as much as possible (Meyer et al. 2000, 2003, Malmiga et al.
260 2014). While doing so, soaring birds tend to take long detours over land (Meyer et al. 2000, Alerstam
261 2001), concentrating in peninsulas, isthmuses and narrow land corridors (Nilsson et al. 2014). Furthermore,
262 the response of migrating raptors to wind conditions is modulated by the geography of their migration
263 route in Southern Italy, with an asymmetric behavioral response of the birds to crosswinds, compensating
264 when winds blew towards the sea and drifting when winds blew towards land (Becciu et al. 2018). Likely
265 the route selection was dependent on wind direction as migration intensity unexpectedly decreased with
266 increasing tailwind assistance, probably because tailwind conditions facilitate a shortcut of the birds over
267 the sea instead of undertaking a long over-land detour (Becciu et al. 2018). A recent broader-scale radar
268 study demonstrated a similar asymmetric response of nocturnally migrating songbirds to crosswinds near
269 the North American Atlantic coast in which the birds drifted when flying over inland areas, but
270 compensated for drift to avoid flying over the ocean near the coast (Horton et al. 2016). Noteworthy, when
271 migrating passerines found themselves offshore at dawn in unfavorable winds for a long overwater flight,
272 they reoriented toward land (Richardson 1978b).

273 Seabirds usually migrate across open waters without apparent barriers to their movements. Under
274 special conditions, such as those experienced when crossing a strait, seabirds may benefit from coastal
275 orographic features during flight, but their response may vary depending on their flight modes. Under
276 moderate winds and whenever visual contact with the coastline is present (as in the case of the Strait of
277 Gibraltar) seabirds changed their course, presumably to better respond to wind conditions. They
278 approached the coast under headwinds proportionally to the magnitude of wind intensity, as a strategy to
279 reduce the effect of headwinds and tended to fly further from the coast under tailwind conditions, to profit
280 from increasing tailwind speed there (Mateos-Rodríguez and Arroyo 2011).

281 HUMAN AND INFRASTRUCTURE DEVELOPMENT: On-the-ground anthropogenic
282 development has consequences on birds engaged in active migration, and radars have been widely used to
283 study the effect of wind turbines and, more recently, light pollution on the movement of migrating birds.
284 Radars provided insight of flight directions, altitudes and speeds of nocturnal migrants near wind turbine

285 facilities (e.g. Mabee et al. 2006, Cabrera-Cruz et al. 2017), with a recent suggestion that bird mortality
286 due to collision with wind turbines occurs regardless of the intensity of the migratory flow (Aschwanden
287 et al. 2018). Radar also assisted assessing the reaction of diurnally migrating birds to wind farms. For
288 example, geese and ducks migrating through the Baltic Sea (Desholm and Kahlert 2005) and raptors and
289 other soaring birds migrating through the Isthmus of Tehuantepec in southern Mexico (Villegas-Patracca et
290 al. 2014, Cabrera-Cruz and Villegas-Patracca 2016) seem to avoid entering newly installed wind farms and
291 change their track accordingly. Artificial lights also disrupt the flight of migrating birds (Cabrera-Cruz et
292 al. 2018), particularly under poor weather and low visibility conditions. For example, nocturnal migrants
293 circled around the steady burning lights of a communication tower during nights with low cloud elevation
294 as opposed to migrants' linear trajectories when no such conditions prevailed (Larkin and Frase 1988).
295 However, if the source of light is bright enough, lights will affect the flight behavior of migrating birds
296 regardless of the weather conditions. For example, Bruderer et al. (1999) demonstrated that nocturnal
297 migrants changed their flight direction by re-orienting themselves $8\pm 10^\circ$ away from a bright light source
298 pointed at them, and that this stimulus also made some birds to decrease their ground speed or change their
299 flight altitude. The drastic effect of the super bright beams of light used during the 9/11 "Tribute in Light"
300 memorial in New York city on nocturnal migrants include the massive bird attraction to the site when lights
301 were on. The birds flew in circles around the beams of light but nonetheless their concentration dissipated
302 and they resumed their normal migratory flight when the lights were turned off (Van Doren et al. 2017).
303 These findings are just a few examples of the extensive research conducted with radar technology which
304 can be used to inform conservation efforts. Hüppop et al. (2019) provide an in-depth review of radar
305 applications to biological conservation of aerial vertebrates, including migratory birds.

306

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