

Assessing the potential impact of wind turbines on the endangered Galapagos Petrel *Pterodroma phaeopygia* at San Cristóbal Island, Galapagos

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Abstract

We evaluated the collision risk of Galapagos Petrels *Pterodroma phaeopygia* with a wind energy development recently constructed in the highlands of San Cristóbal Island, Galapagos. Trained observers recorded the movements of petrels at dusk and dawn from the wind project site, and from control sites located along ravines that host nesting colonies. Collision mortality was also assessed by monitoring circular plots and transect lines located under human-made structures. Petrel flight activity showed a bimodal pattern, with the majority of the movements recorded in the hours previous to sunrise. Most petrels (96%) moved along major ravines that descend from the highlands to the south-southeastern coast of the island. Significant differences in passage rates were found between the project and control sites, with only five petrels recorded on the site selected for turbine installation. Although our data suggest that wind farms will not be more detrimental to petrels than other existing man-made structures, a word of caution is made because even very low levels of additional mortality might be significant for a species with such low productivity and slow maturation rates. Moreover, some other possible indirect effects on habitat change and disturbance might occur that were not assessed in our study. A post-construction monitoring program should be implemented to adequately assess long-term effects on petrels and to enable these uncertainties to be satisfactorily addressed.

Keywords: Collision risk, Flight patterns, Galapagos Islands, Galapagos Petrel, Wind turbines.

INTRODUCTION

Wind farms are receiving strong public support as an alternative “clean” energy source, being currently one of the fastest growing energy sectors in the world (EWEA 2009). However, wind energy developments are not exempt from conservational drawbacks, with the potential impact of wind turbines on birds being one of the areas of major concern (Leddy et al. 1999; Drewitt and Langston 2006; Everaert and Stienen 2007).

Effects of wind-energy facilities on birds can be grouped into direct impacts resulting from flying birds being killed directly by collisions with rotating turbine blades or monopoles, and indirect impacts referring to disruption of breeding activities, foraging behavior or flight patterns due to disturbance, and habitat change or loss (Desholm et al. 2006; Drewitt and Langston 2006; Kunz et al. 2007; Larsen and Guillemette 2007). These impacts can potentially alter demographics, genetic structure, and population viability of threatened and endangered species or species of special concern (NRC 2007).

Various studies have shown that the scale of wind power-related avian fatalities and disturbance effects vary greatly depending on a wide range of factors including the species, spatial and temporal activities of birds, location with respect to important nesting or foraging habitats, availability of alternative habitats, turbine and wind farm specifications and operational status, or wind force and direction (Erickson et al. 2001; De Lucas et al. 2004; Desholm and Kahlert 2005; Stewart et al. 2007; Drewitt and Langston 2008).

The Galapagos Islands are among the most renowned and best preserved natural sites in the world (Bensted-Smith 2002; González et al. 2008). One of the issues of major concern to the Ecuadorian conservation authorities is the high risk of possible fuel spills and their potential effects on the fragile environment of the archipelago. These concerns

proved to be valid when the oil tanker “Jessica” ran aground in the harbor of San Cristóbal, spilling significant amounts of fuel in January 2001. Diesel fuel is currently used in the four inhabited islands of the archipelago (Santa Cruz, San Cristóbal, Isabela, and Floreana) to power diesel generators that produce electricity needed by local residents.

Some initiatives to replace the existing diesel combustion generated power with clean energy are being developed. One of the most outstanding is the San Cristóbal Wind Project (SCWP) which has as its main objective to replace, as much as technically and economically feasible, the diesel-powered generation with wind energy, reducing the environmental risks caused by the current system. However, preliminary feasibility studies suggested that several bird species could be potentially affected by the SCWP project. The Galapagos Petrel *Pterodroma phaeopygia* would likely be the species most sensitive to increased mortality as a result of collision, with the risk being greater when turbines are located close to the breeding colonies or when they intercept local flight paths between nesting and feeding areas.

The Galapagos Petrel is endemic to the Galapagos Archipelago where it is known to breed only on five islands: Floreana, San Cristóbal, Santa Cruz, Isabela, and Santiago. Nesting occurs only in the humid highlands, where native vegetation cover is dense (Harris 1970; Coulter 1984; Coulter et al. 1985). All the breeding populations have been seriously reduced through predation by introduced mammals and destruction of nesting habitat (Coulter et al. 1985; Tomkins 1985; Cruz and Cruz 1987; Cruz-Delgado et al. *in prep.*). Given the reduced nesting success and the limited distribution, the Galapagos Petrel was added to the IUCN Red Data Book as a Critically Endangered species (Hilton-Taylor 2000; Granizo et al. 2002).

The population of petrels nesting in San Cristóbal is probably the most threatened, with two major factors contributing to this situation (Cruz-Delgado et al. *in prep.*). On one hand, nesting habitat has been reduced and degraded as a consequence of agricultural activities and introduced blackberry (*Rubus* spp.) expansion; almost 93% of the humid highland ecosystems of the island has been transformed and occupied for agriculture (Snell et al. 2002). On another hand, abnormally high mortality rates of eggs and nestlings caused by introduced rat (*Rattus* spp.) predation severely limits reproductive success (Cruz-Delgado 2005). The fact that more than 90% of the nest burrows are on privately-owned agricultural lands located outside the boundaries of the National Park is another factor of major worry.

In this paper we analyze the movements and flight patterns (altitude and orientation of flight, timing, frequency, etc.) of Galapagos Petrels in the vicinity of the hill selected for turbine installation (hereafter, the “project site”), as well as in the major ravines that host nesting colonies of the species (used as “control sites” for comparison). The ultimate goal of our study was to evaluate the potential impacts of the SCWP on the local Galapagos Petrel population, while contributing to the detection of critical areas for petrel movement in which future wind turbines should be avoided.

METHODS

Study area

The Galapagos archipelago straddles the equator, approximately 960 km west of mainland Ecuador and 1,100 km south of Costa Rica. It comprises seven major islands (>100 km²),

11 smaller islands ($>1 \text{ km}^2$) and more than 120 islets and rocks. San Cristóbal Island is the fifth largest of the archipelago, covering 55,709 ha. Almost 84% of it is protected as a part of the Galapagos National Park, with the rest occupied by agricultural lands and the coastal village of Puerto Baquerizo Moreno (Fig. 1).

There are two distinct climatic seasons in Galapagos. During the cool-dry season (locally called *garúa* season), from June to December, there is prolonged cloud cover and perpetual drizzle in the highlands, and no rain in the lowlands, with temperatures ranging between 19-23°C. Contrarily, the warm-wet season, from January to March, is usually characterized by sunny skies with occasional heavy rains, and temperatures ranging from 24-29°C.

The San Cristóbal Wind Project

The SCWP seeks to install a wind-diesel hybrid system on San Cristóbal Island, to reduce the amount of diesel fuel currently used and to promote the introduction of renewable energies into the archipelago (www.galapagoswind.org). The SCWP is being implemented by members of a consortium composed of electricity companies that operate in the national territories of the G8 countries, in partnership with the local electric utility in the Galapagos and in coordination with the United Nations Development Programme (UNDP).

The project includes the installation of three 800 kW wind turbines, with 59 m diameter blades and 51.5 m hub height; therefore, the tip of the blades at their lowest point are 23.5 m above ground. Preconstruction environmental assessments for the project recommended that the originally proposed wind turbine site at Cerro San Joaquín, the highest peak on the island, was not adequate due to the close presence of many active

Galapagos Petrel nests and so other potential sites were explored, concluding in the selection of Cerro El Tropezón as the most appropriate location for turbine installation (see Fig. 1). Construction of the wind facility ended in August 2007, and turbines began a phase of test operation in September 2007.

Flight patterns

Observations were conducted during two periods, from June to October 2004 and from February to March 2005, corresponding to the two major climatic seasons. A total of 50 sample points were established, 43 in the flanks of the main ravines hosting nesting colonies, and seven on the proposed location for wind turbines in the SCWP feasibility analysis. Points were selected to minimize interference by vegetation and wind noise, and to improve petrel detectability. A total of 400 hours of observation were completed in the project site, and 446 in the control sites located along ravines.

Two trained teams of observers recorded the movements of petrels at dusk (one hour before and two hours after sunset) and dawn (3 hours before sunrise), synchronously at project and control sites. Those periods were chosen because a bimodal flight pattern between the nesting colonies and the sea had been previously reported (Cruz and Cruz 1990), with dusk and dawn periods being the more active. Nine all-night observation periods conducted at the beginning of our study also confirmed this bimodal pattern. To record bird movements, we used a combined methodology of night visual observations with high resolution image intensifiers (Swarovski 3x night vision monoculars) and acoustic detection to monitor bird movement from their calls (Evans 2000). Nocturnal flight calls of Galapagos Petrels are easy to identify and no confusion with other species is likely to

occur. Acoustic recording equipment was used during the preliminary tests with poor results, so it was decided to rely on expert listening by trained personnel. The use of radar was not considered due to the lack of available equipment and expertise, and also to the difficulties for species identification and its limitations of usage under the rainy and foggy weather conditions that predominate in the study sites (Drewitt and Langston 2006; Kunz et al. 2007). A total of 145 dawn counts and another 145 dusk counts (total = 846 hours of observation) were completed to investigate the Galapagos Petrel's flight patterns.

Petrel movements were mapped using a series of landscape points of reference (e.g., hills, ravines, paths, roads, etc.) located in the vicinity of the observation sites. The origin of the birds was also recorded (using the first point in which the bird was detected), as well as the flight direction (using the closest point where a movement could be established), and the time of the day (hour/minutes). Recording time was normalized to minutes past sunset or minutes to sunrise, to facilitate pooling and comparing data throughout the year. Flight altitude was recorded for visual contacts, using elevation angles and benchmarks located on ravines and hills. Bird contacts were distributed on three vertical bands: below rotor swept area, within rotor swept area, and above rotor swept area. To reduce bias, flight altitudes were analyzed separately according to the location of the observation point (top, middle or lower part of the ravine or hill).

A total of 682 contacts were used in most of the analyses. However, 228 (39.1%) of acoustic records could not be precisely mapped because of the low intensity of the calling, and were not included in the assessment of flying routes. Another 39 visual records were not clear enough due to low visibility and were also excluded.

As there were no significant differences between counts made in the two climatic seasons (Mann-Whitney test; $U = 9481$; $P = 0.321$), data were pooled together for the

analyses. An index of flight frequency was obtained as the percentage of count periods in which petrel movements were recorded. We also estimated the number of flights per year using the flight frequency and the average number of contacts recorded per hour and observation point.

Weather conditions such as the presence/absence of drizzle, visibility, and cloudiness were recorded at 30 min intervals for each of the count periods. Data on wind direction and wind speed were also gathered from a weather station installed in the project site at Cerro El Tropezón.

For comparisons among the different areas, data on passage rates were standardized to number of contacts per hour per sample point, separately for dawn and dusk counts. Mann-Whitney *U*, Kruskal-Wallis, and Chi-square tests were used to compare frequencies, passage rates, and flight altitudes among different locations. Kruskal-Wallis tests and Spearman correlation rank were used to test the influence of different weather conditions on passage rates.

Bird collision risk

To estimate the potential future mortality caused by collision with turbines, we assessed current rates of bird mortality caused by collision with other human-made constructions already present in the study area. Thirteen 50 m-radius circular plots were established under different types of structures, including three communication masts, four weather stations, and six radio antennas, located in the highlands of San Cristóbal. In addition, nine 100 x 20 m transects were established under seven power lines located near the major petrel nesting colonies. All these plots and transects were inspected twice a month, except the plot under a

weather station located in the project site, which was inspected once a week. Globally, an area of 7.05 ha was sampled over 147 days.

Several parameters were recorded for each carcass found, including species, age, sex, estimated number of days since death, distance to the nearest human-made structure, and type of infrastructure that probably caused the death. Based on the number of carcasses found throughout the study period under each structure, an estimation of the annual mortality rate per human-made structure was derived.

Carcass searches can be helpful but have limited efficiency because factors such as vegetation type, scavenger density, carcass size and terrain influence the outcome (Dieter et al. 2000). Thus lack of reliable correction factors for biases associated with searcher efficiency and scavenging make it difficult to derive reliable estimates of mortality (Morrison 2002; Kunz et al. 2007). To derive a correction factor for the permanence of carcasses and the removal rate by scavengers, we placed eight medium-size carcasses (*Bubulcus ibis*, *Crotophaga ani*, *Pterodroma phaeopygia*) and five small carcasses (*Geospiza spp.*) in areas with different vegetation cover, and their condition was monitored every 2-7 days for one month. Carcasses were obtained from roadkills or collisions with human-made structures.

RESULTS

Flight patterns

A total of 682 contacts of petrels in flight were recorded. Overall, most of the movements (87.1%) occurred at dawn, with only 12.9% of records at dusk (Table 1). However, there

was a difference between visual and acoustic contacts. At dawn 78.3% of the records corresponded to acoustic contacts and 21.7% were visual contacts; at dusk 61.4% were acoustic and 38.6% visual.

Petrel flight activity began one hour before sunset, reaching a peak two hours later (46 of 88 records) when it became darker (Fig. 2). Towards the end of the night a new increase in flying activity was observed, with the highest number of movements taking place between 120 and 60 min before sunrise (438 of 594 records). After that, the number of movements decreased rapidly with daylight (Fig. 2).

Most petrels moved along major ravines that descend from the highlands to the south-southeastern coast of the island (Fig. 3). The large majority of the movements were recorded between the southern coast of San Cristóbal and the nesting colonies. Most of the records (67%) corresponded to petrels flying from the nesting colonies to the southern coast of the island. 29.4% of the records were petrels moving from the southern coast to the nesting colonies. Only 3.6% of the records (15 contacts) corresponded to petrels flying between the northern coast of the island and the colonies.

Two areas of massive occurrence and activity of birds were located in the ravines that descend to the southern coast (Fig. 3), probably corresponding to courtship areas. In these sites, groups of petrels were observed flying at different altitudes for periods of time ranging from 17 to 109 min (mean: 66 min) in a ca. 200 m-radius circular areas.

Significant differences in passage rates were found between sample points located in the project site and the rest of the sampling sites monitored (Mann-Whitney test, $U = 272.5$, $P = 0.003$). Only five petrels (0.73%) were recorded on the selected site for turbine installation at Cerro El Tropezón in a total of 400 hours of observation, indicating that

passing rates through the project site are very low in comparison to the control-sites (Table 1).

The flight frequency index at the project site was 0.04. The mean number of flights recorded per hour and per sample point was 0.005 (SD = 0.010; range: 0 - 0.028). From these data, an estimation of 1.8 movements per sample point was derived for a whole year (95% CI: 0 – 13.9) at the project site (Table 1).

At the control sites, the flight frequency index ranged between 0.41 and 0.80, with a mean number of flights per hour per sample point ranging between 0.35 and 1.34. The overall frequency index for all the control sites was 0.56, with a mean number of 1.36 flights recorded per hour and per site (SD = 2.04; range: 0 - 12.18). An average annual estimation of 601.7 movements per sample point was obtained for a whole year (95% CI: 237.6 – 1521.4).

No significant correlations were found between the number of petrel movements recorded and climatic variables such as average wind speed (Spearman correlation test, $r_s = 0.001$, $P = 0.388$), cloud cover (Kruskal-Wallis test, $\chi^2 = 10.62$, $df = 3$, $P = 0.156$), or wind direction (Kruskal-Wallis test, $\chi^2 = 2.85$, $df = 3$, $P = 0.415$). However, a significantly larger number of petrel flights were recorded during hours with drizzle (Mann-Whitney test, $U = 44369$, $P = 0.019$).

The band below the rotor swept area was the most frequently used by petrels in the study area. Although there were significant differences in the recorded flight altitudes among the various points of observation (Chi-square test, $\chi^2 = 29.5$, $df = 12$, $P = 0.003$), overall, 70.8% of the petrels were flying below the range of movement of turbine blades. Only 18.8% of the petrels were recorded flying in the range of the rotor-swept zone (Fig.

4). The number of flight altitudes recorded in the project site was too small to establish solid comparisons with the control sites.

Bird collision mortality

Galapagos Petrel mortality associated with human-made structures does exist at San Cristóbal, as revealed by our collision-mortality sampling. Two Galapagos Petrels died as a result of a collision with two power lines, one located in a ravine and the other on the base of a hill, both close to the nesting colonies. Another Galapagos Petrel collided with the support cables of a group of radio antennas located in a private property. Fatalities of other species of birds were also recorded during the study: a Magnificent Frigatebird *Fregata magnificens* collided with a communication mast under conditions of low visibility caused by foggy weather, and seven Small Ground-Finches *Geospiza fuliginosa* died as a consequence of a strike with support cables of a weather station. Carcasses of medium-large size birds all showed wing fractures, while small birds presented injuries in different body parts.

Our data resulted in an estimation of average petrel annual mortality of 0.21 individuals per structure per year (95% CI: 0 – 0.54). No correction factor was applied to these estimations, as previous tests to estimate searcher and scavenging biases resulted in none of the medium-large size carcasses disappeared during one month of monitoring and no signs of scavenging were noticeable. Only one small carcass was removed and not located in the following visit. Nine carcasses remained in the same place for more than three weeks, with no sign of scavenging. Another three finch carcasses remained in the area

for around two weeks. All carcasses became dried after a few days, with no removal or scavenging signs.

DISCUSSION

Flight patterns

Daylight highly influences flight activity of petrels at San Cristóbal, which shows a clear bimodal pattern. This pattern is consistent with that observed in other islands of the archipelago (Cruz and Cruz 1990), and in other procellariids (Day and Cooper 1995; Cooper and Day 2003). This is also consistent with the observation that full moon nights with clear sky contribute to a lesser number of petrel movements (Warham 1990).

We found the majority of petrel movements in the hours previous to sunrise, which is consistent with the much larger number of petrels captured during that period using mist nets in Santa Cruz (Podolsky and Kress 1992). However, our results could be influenced by a different calling behaviour of petrels. Differences between acoustic contacts during dawn and dusk could be attributed to the fact that birds tend to call more often during dawn (Cruz-Delgado, *pers. obs.*). Previous observations on the calling behavior of Galapagos Petrels showed that movements after sunset are usually more silent in comparison with hours close to dawn (Tomkins and Milne 1991). Our data confirm this, with much higher acoustic contacts and larger calling activity at courtship areas right before dawn. However, in other nesting areas of the archipelago such as Cerro Pajas on Floreana Island, petrels tend to call during flights in hours close to the sunset (Cruz-Delgado, *pers. obs.*).

There is scarce information about flying routes for Galapagos Petrels. Data on similar species suggest that petrels fly following the main valleys (Ainley et al. 1997; Podolsky et al. 1998). This is confirmed by our observations in San Cristóbal, where most of the recorded movements were along ravines oriented to the south-southeast of the island.

Regarding flight altitudes, our results show that onshore, petrels tend to fly below the rotor swept zone, although in the courtship areas flights above 40 m high were also quite common. Harris (1970) reported flying heights between 70 and 100 m for petrels crossing the coast line. Our observations indicate that petrels fly well above 150 m when flying to the sea from the upper parts of the island, but usually cross the coast line below 100 m high when returning to the nesting areas from the sea.

Weather conditions could be expected to influence petrel flight patterns (Podolsky et al. 1998). However, except for drizzle, we found no statistical relation between several weather variables and the frequency of flights. Podolsky and Kress (1992) also did not find any influence of weather conditions on the movements of petrels in Santa Cruz Island. It is remarkable that some procellarids are able to fly even under severe weather conditions (Grant et al. 1983). We recorded petrel movements under conditions of minimal visibility and completely covered sky accompanied with dense drizzle, which demonstrates their ability to orientate to their nests even in low-visibility conditions.

Collision mortality

Studies conducted in Hawaii revealed that, among human-made structures, power lines have the highest potential for causing mortality to Hawaiian Petrels, particularly when these lines crossed valleys (Podolsky et al. 1998). Our results are consistent with this statement

as two Galapagos Petrels died as a result of collision with power lines. We also observed the negative influence of tension-support cables of communication towers or radio antennas, which caused another petrel fatality during the study period. An additional petrel death was reported but could not be confirmed by the authors. This effect could be particularly dramatic when several towers are concentrated in the same area, and when they are located close to the nesting colonies or the flying paths. Additional observations at Santa Cruz Island indicated that new power lines constitute a serious risk to the petrels: in September 2004 two petrels collided with a newly-constructed electrical distribution line built perpendicular to their flight route about 1.5 km south of Bellavista at an elevation of 150 m above sea level (Wiedenfeld, *pers. obs.*). It is possible that the petrels over time will learn the locations and avoid structures, but newly-built tall structures pose a high risk because of the petrels' unfamiliarity with them.

Light-induced mortality has been reported in other procellarids, as birds in flight might be disoriented by different sources of artificial light (Grant et al. 1983; Le Corre et al. 2002). This might explain at least two of the collisions recorded during our study. The effect of lights can be particularly important during the fledgling period, when young birds might become disoriented by artificial lights during their first flight to the ocean, and fall to the ground exhausted or killed by collision with urban structures (Podolsky et al. 1998).

Petrel nesting phenology might also affect collision risk, as the birds' vulnerability to new wind energy developments could be different depending on the stage of the breeding cycle. Tomkins and Milne (1991) have shown that nesting takes place over a very prolonged period of the year in San Cristóbal, with laying dates extending from November to August (Cruz-Delgado 2005). This fact has certain implications for analyzing collision risk, as the presence of breeding petrels in San Cristóbal highlands is almost continuous

throughout the year, contrary to what happens in other islands of the archipelago where the breeding season is much shorter (Cruz and Cruz 1990; Tomkins and Milne 1991).

Other species of birds, particularly passerines, are also highly affected by the tension-support cables of weather stations, especially in windy areas. Seven individuals were found dead under these structures during periods of great wind speed. Other structures without support cables probably have lower impact on birds: only one large-size bird collided with a communication tower, probably under conditions of low visibility.

Despite the presence of feral cats and introduced rats in the surroundings of some structures, which might suggest potential scavenging on collided birds, no carcasses disappeared or showed evidence of being eaten by predators during our monitoring activities. However, two factors regarding these results need to be taken into consideration: (1) birds that are wounded but remain alive for several days may be more detectable and attractive to feral cats, dogs or rats than are dead birds, which will begin to decompose a few hours after their deaths as a result of temperature and humidity conditions; and (2) the effect of feral cats may have been reduced because of a possible seasonal migration to the lowlands (Cruz-Delgado, *pers. obs.*). For these two reasons the indicators of collision mortality need to be tested with more data, especially on the persistence of injured birds.

Caveats

As most of the methods applied to the study of nocturnal flight behavior, our approach has certain technical limitations that should be acknowledged. No single method or protocol can be used to assess the impacts of wind turbines on nocturnally active birds (Anderson et al. 1999). Each device or method has its own strengths, limitations, and biases (Kunz et al.

2007). Our estimates of flight altitude may be biased due to the greater probability of visually detecting lower flying birds and the general difficulty of visually estimating flight altitude. Another potential limitation refers to changes in bird detectability under different conditions of cloud cover, drizzle, or foggy weather. A final constraint relates to the fact that flight calls or visual contacts cannot be directly extrapolated to estimate the number of birds flying, as it is unknown how often the birds call, or if the same bird was recorded more than once over the same observation period.

Previous training was necessary to get accurate estimations of distances and flight altitudes. In spite of that, difficulties still arose, particularly under low visibility conditions. Thus, getting reliable fly-paths for mapping was complicated and only those bird contacts recorded under good visibility and weather conditions could be used for the construction of routes.

Another element of concern is the fact that our work has concentrated exclusively on the possible impact of turbines on birds, but other indirect impacts of auxiliary infrastructure were not assessed. Wind farms comprise the wind turbines themselves, interconnecting cables, transformer stations, meteorological masts and ancillary infrastructure including access roads. These structures might represent an even larger potential threat to wildlife than the turbines themselves because they can result in habitat fragmentation and facilitate the invasion by new exotic species (Kuvlesky et al. 2007). Fortunately, in the SCWP project the majority of the cables in the area where the petrels occur were buried, reducing the effects of that source of mortality.

Implications for conservation

Apparently Cerro El Tropezón is not an area frequently transited or used by petrels, which prefer to use ravines oriented to the south-southeast of the island for their movements between the colonies and the sea. This suggests that collision risk with wind turbines will be low at the site selected for turbine location, and that Galapagos Petrels probably will not be affected by the SCWP wind farm more than by other human-made structures already present on the island. This is consistent with other studies that found structures such as power lines more harmful to birds than wind turbines (Nelson and Curry 1995; Osborn et al. 1998; Drewitt and Langston 2008). Moreover, recorded flight altitudes suggest that petrels are not particularly vulnerable to the turbines as most of the birds onshore flew below the height range of the rotor-swept zone.

It also appears that turbines will not have a barrier effect, as they do not block a regularly used flight line between nesting and foraging areas. The scale of direct habitat loss resulting from the construction of the wind farm is estimated to be very small, as the three turbines and associated infrastructure occupy only 4 ha (CONELEC 2006).

Despite this, it has to be acknowledged that possible indirect effects on habitat change and disturbance might occur, and these were not assessed in our study. Wind turbines may not physically exclude birds from the habitat but may make the habitat less desirable. This could be a serious limitation when nesting habitat availability is scarce, as is the case in San Cristóbal (Cruz-Delgado 2005).

Another word of caution should be made regarding the apparent lack of direct effect of wind turbines. Accepting that the SCWP wind farm will likely result in only low levels of mortality, even these levels of additional mortality might be significant for a species of high conservation concern, such as the Galapagos Petrel. Endangered long-lived species, with low productivity and slow maturation rates, can be especially affected by even small

increases in mortality of adult birds, because of already low population numbers (Drewitt and Langston 2006). In this sense, the loss of a few breeding Galapagos Petrels could be detrimental to an already vulnerable population and the effects at the population level could be significant. Moreover, it must be noted that for a long-lived, highly philopatric species, like the Galapagos Petrel (Cruz and Cruz 1990), the disturbance effects caused by wind turbines might not be evident in the short term and true impacts might only be evident after many years when new recruits are needed to replace existing breeding birds (Drewitt and Langston 2006).

The construction of the San Cristóbal wind-energy facility ended in August 2007, and turbines began a phase of test operation in September 2007. A monitoring program has been carried out since, with fatality searches conducted on a systematic schedule of three days during the first month, once a week during the two following months, and once every fifteen days thereafter. In the seven months after the beginning of operations no bird fatalities have been recorded in the wind farm (Walsh Ecuador, *unpubl. report*). However, the fact that three petrels were found dead at other man-made structures in the highlands of San Cristóbal during our previous study shows that some mortality might eventually occur at wind farms. Risks are also increased because of the foggy weather conditions that predominate in the highlands of San Cristóbal for most of the year. Several studies have demonstrated that collision risk increases when visibility is poor, as on foggy or rainy days (Erickson et al. 2001; Kingsley and Whittam 2001).

On the other hand, postconstruction monitoring revealed two bat (*Lasiurus borealis brachyotis*) fatalities as a consequence of a collision with turbines in the project site (Walsh Ecuador, *unpubl. report*). This fact is also of great concern, particularly because the bats are

of an endemic subspecies. Several studies have reported extensive fatalities of bats at wind turbines (Arnett et al. 2008).

Some recommendations emerging from our results might be of interest for this and other future wind farms in the Galapagos Islands, as well as in other oceanic archipelagos hosting different species of endangered procellariids that could be potentially affected by new wind energy developments.

It appears that wind turbines without support cables might not be a high risk for petrels if properly located after a careful study of flight patterns. However, other human-made structures such as weather stations or antennas with support cables installed on the project site might have a larger impact than wind turbines themselves. This impact can be particularly severe when infrastructures are combined with artificial lights (Drewitt and Langston 2008). Therefore the construction of this kind of infrastructure should be minimized, and the use of lights should be restricted to avoid fledging mortality.

Other evidence also shows that power lines pose an important risk for flight movements, especially when they cross ravines or highly used flying routes. Particular care should therefore be put into the design and construction of the power lines between wind turbines and the main electric power station. An option to reduce collision risk is to bury the power lines or at least those segments that cross ravines and nesting colonies (as has been done with the first 3 km of power line in San Cristóbal).

Compensation measures should also be implemented, including the use of poison to control rats in the nesting colonies, as they constitute the main cause of nesting failure and the main threat to Galapagos Petrel populations (Cruz and Cruz 1990). A progressive program should be implemented to remove or modify human-made infrastructures either located close to nesting colonies or interfering with petrel flight paths.

Finally, a post-construction monitoring program to assess mortality associated with the different infrastructures is necessary to adequately evaluate the effects of wind energy developments (Fox et al. 2006). Monitoring should extend in time long enough to identify both short- and long-term effects and to enable these to be satisfactorily addressed. The program should also include research on nest occupancy and reproductive success in colonies located close to the wind energy infrastructures, and be integrated with targeted research on biology of the Galapagos Petrel to address critical points not yet solved such as preferred foraging areas, population genetic structure, and effective methods to control invasive species at nesting colonies (Friesen et al. 2006; Cruz-Delgado 2005).

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REFERENCES

- Ainley DG, Podolsky R, DeForest L, Spencer G (1997) New insights into the status of the Hawaiian Petrel on Kauai. *Col Waterbirds* 20:24-30
- Anderson R, Morrison M, Sinclair K, Strickland D (1999) Studying wind energy-bird interactions: a guidance document. Avian Subcommittee and National Wind Coordinating Committee. Available at http://www.nationalwind.org/publications/wildlife/avian99/avian_booklet.pdf. Cited 9 Apr 2009
- Arnett EB, Brown WK, Erickson WP, Fiedler JK, Hamilton BL, Henry TH, Jain A, Johnson GD, Kerns J, Koford RR, Nicholson CP, O'Connell TJ, Piorkowski MD, Tankersley RD (2008) Patterns of bat fatalities at wind energy facilities in North America. *J Wild Manag* 72:61-78
- Bensted-Smith R (ed) (2002). A biodiversity vision for the Galapagos Islands. Charles Darwin Foundation and World Wildlife Fund, Galapagos, Ecuador
- CONELEC (2006) Resolución No DE-06-001. Consejo Nacional de Electricidad, Ecuador
- Cooper B, Day R (2003) Movement of the Hawaiian Petrel to Inland Breeding Sites on Maui Island, Hawaii. *Waterbirds* 26:62-71
- Coulter MC (1984) Seabird conservation in the Galapagos islands, Ecuador. *ICBP Tech Publ* 2:237-244
- Coulter MC, Cruz F, Cruz JB (1985) A programme to save the Dark-rumped Petrel, *Pterodroma phaeopygia*, on Floreana Island, Galapagos, Ecuador. *ICBP Tech Publ* 3:177-180

- Cruz JB, Cruz F (1987) Conservation of the Dark-rumped Petrel *Pterodroma phaeopygia* of the Galapagos Islands, Ecuador. Biol Conserv 42:303-311
- Cruz F, Cruz JB (1990) Breeding, morphology, and growth of the endangered Dark-Rumped Petrel. Auk 107:317-326
- Cruz-Delgado F (2005) Biología reproductiva de *Pterodroma phaeopygia* (Procellariidae), Isla San Cristóbal, Galápagos. Dissertation, Universidad Central del Ecuador, Quito
- Day RH, Cooper BA (1995) Patterns of movement of dark-rumped petrels and Newell's shearwaters on Kauai'i. Condor 97:1011-1027
- De Lucas M, Janss GFE, Ferrer M (2004) The effects of a wind farm on birds in a migration point: the Strait of Gibraltar. Biodivers Conserv 13:395-407
- Desholm M, Kahlert J (2005) Avian collision risk at an offshore wind farm. Biol Let 1:296-298
- Desholm M, Fox AD, Beasley PDL, Kahlert J (2006) Remote techniques for counting and estimating the number of bird-wind turbine collisions at sea: a review. Ibis 148:79-89
- Drewitt A, Langston R (2006) Assessing the impacts of wind farms on birds. Ibis 148:29-42
- Drewitt A, Langston R (2008) Collision effects of wind power generators and other obstacles on birds. Ann NY Acad Sci 1134:233-266
- Dieter CD, Higgins KF, Nieger RD, Osborn RG, Usgaard RE (2000) Bird mortality associated with wind turbines at the Buffalo Ridge Wind Resource Area, Minnesota. Am Midl Nat 143:41-52
- Erickson WP, Johnson GD, Strickland MD, Young DP, Sernja KJ Jr, Good RE (2001) Avian collisions with wind turbines: a summary of existing studies and comparisons to other sources of avian collision mortality in the United States. Western EcoSystems Technology Inc., National Wind Coordinating Committee Resource Document.

Available at http://www.nationalwind.org/publications/wildlife/avian_collisions.pdf.

Cited 9 Apr 2009

Evans WR (2000) Applications of acoustic bird monitoring for the wind power industry. In Proceedings of the National Avian-Wind Power Planning Meeting III, San Diego, California, May 2000. Prepared for the National Wind Coordinating Committee. L.G.L. Ltd., Ontario.

Everaert J, Stienen EWM (2007) Impact of wind turbines on birds in Zeebrugge (Belgium) – Significant effect on breeding tern colony due to collisions. *Biodivers Conserv* 16:3345-3359

EWEA (2009) Wind energy – The facts. The European Wind Energy Association, Brussels. Available at <http://www.ewea.org>. Cited 9 Apr 2009.

Friesen VL, González JA, Cruz-Delgado F (2006) Population genetic structure and conservation of the Galápagos petrel (*Pterodroma phaeopygia*). *Cons Gen* 7:105-115

Fox AD, Desholm M, Kahlert J, Christensen TK, Petersen IK (2006) Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. *Ibis* 148:129-144

González JA, Montes C, Rodríguez J, Tapia W (2008) Rethinking the Galapagos Islands as a complex social-ecological system: implications for conservation and management. *Ecol Soc* 13(2):13

Granizo T, Pacheco C, Rivadeneira M, Guerrero M, Suárez L (2002) Libro Rojo de las aves del Ecuador. Serie Libros Rojos del Ecuador, vol 2. Simbioe, Conservación Internacional, Ecociencia, Ministerio del Ambiente, and UICN, Quito, Ecuador

Grant G, Warham J, Pettit T, Whittow C (1983) Reproductive behavior and vocalizations of the Bonin Petrel. *Wilson Bull* 95:522-539

- Harris M (1970) The biology of an endangered species, the Dark-rumped Petrel (*Pterodroma phaeopygia*), in the Galapagos Islands. *Condor* 72:76-84
- Hilton-Taylor C (ed) (2000) The 2000 IUCN Red List of threatened species. IUCN, Gland, Switzerland, and Cambridge, UK
- Kingsley A, Whittam B (2001) Potential impacts of wind turbines on birds at North Cape, Prince Edward Island. Bird Studies Canada, Sackville, New Brunswick
- Kunz TH, Arnett EB, Cooper BM, Erickson WP, Larkin RP, Mabee T, Morrison ML, Strickland MD, Szewczak JM (2007) Assessing impacts of wind-energy development on nocturnally active birds and bats: a guidance document. *J Wild Manag* 71:2449-2486
- Kuvlesky WP Jr, Brennan LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC (2007) Wind energy development and wildlife conservation: challenges and opportunities. *J Wild Manag* 71:2487-2498
- Larsen JK, Guillemette M (2007) Effects of wind turbines on flight behaviour of wintering common eiders: implications for habitat use and collision risk. *J Appl Ecol* 44:516-522
- Le Corre M, Ollivier A, Ribes S, Jouventin P (2002) Light-induced mortality of petrels: a 4-year study from Réunion Island (Indian Ocean). *Biol Conserv* 105:93-102
- Leddy K, Higgins K, Naugle D (1999) Effects of wind turbines on upland nesting birds in Conservation Reserve Program Grasslands. *Wilson Bull* 111:100-104
- Morrison ML (2002) Searcher bias and scavenging rates in bird-wind energy studies. National Renewable Laboratory Report NREL/SR-500-30876, Golden, Colorado. Available at <http://www.nrel.gov/wind/pdfs/30876.pdf>. Cited 10 Oct 2008

- Nelson HK, Curry RC (1995) Assessing avian interactions with windplant development and operation. Trans N Am Wildl Nat Resour Conf 60:266-287
- NRC (National Research Council) (2007) Environmental impacts of wind-energy projects. The National Academies Press, Washington DC
- Osborn RG, Dieter CD, Higgins KF, Usgaard RE (1998) Bird flight characteristics near wind turbines in Minnesota. Am Midl Nat 139:20-38
- Podolsky R, Ainley DG, Spencer G, Deforest L, Nur N (1998) Mortality of Newell's shearwaters caused by collisions with urban structures on Kauai. Col Waterbirds 21:20-34
- Podolsky R, Kress S (1992) Attraction of the Endangered Dark-rumped Petrel to Recorded Vocalizations in the Galapagos Islands. Condor 94:448-453
- Snell HL, Tye A, Causton CE, Bensted-Smith R (2002) Current status of and threats to the terrestrial biodiversity of Galapagos. In: Bensted-Smith R (ed) A biodiversity vision for the Galapagos Islands. Charles Darwin Foundation, and World Wildlife Fund, Galapagos, Ecuador, pp 30-47
- Stewart GB, Pullin AS, Coles CF (2007) Poor evidence-base for assessment of windfarm impacts on birds. Env Cons 34:1-11
- Tomkins R, Milne B (1991) Differences among dark-rumped petrel (*Pterodroma phaeopygia*) populations within the Galapagos Archipelago. Notornis 38:1-35
- Tomkins R (1985) Breeding success and mortality of dark-rumped petrels in the Galapagos, and control of their predators. ICBP Tech Publ 3:159-175
- Warham J (1990) The Petrels. Their Ecology and Breeding Systems. Academic Press, London

FIGURE CAPTIONS

Fig. 1 Location map of the study area showing the selected site for the wind farm at Cerro El Tropezón, and other related infrastructures.

Fig. 2 Patterns of daily flight activity in relation to sunset and sunrise.

Fig. 3 Major flight routes and flight directions of petrels recorded at San Cristóbal, showing the position of sample points, as well as the major nesting colonies of the species, and possible courtship areas. Thick solid lines are the main observed flight paths and dashed lines are probable flight paths to the colonies, taking into account that birds usually follow major ravines.

Fig. 4 Estimated flight altitude of petrels, sorted according the location of the observation point and the height of the rotor swept area (RSA).

Table 1 Index of flight frequency and number of bird movements recorded from the sample points located at the project site (Cerro El Tropezón) and the control sites (ravines and nesting colonies).

	Control sites near to SCWP					Control sites far from
	SCWP site		Control sites near to SCWP			SCWP
	Cerro		Represa			El Junco, La Comuna, Ángel Guamanquishpe,
	El Tropezón	El Plátano	La Toma	Antigua	San Joaquín	Carmela Palma
N° sample points	7	16	8	4	5	10
Total observation periods	137	76	31	12	12	22
Observation periods with petrels	5	37	25	5	6	14
Frequency Index	0.036	0.487	0.806	0.417	0.500	0.636
N° petrel movements recorded	5	359	214	12	16	76
Total hours of observation	400	224,5	90	34	34	63,5
Petrel flights per hour per sample point (Mean±SD)	0.005 ± 0.01	0.997 ± 1.11	3.047 ± 3.86	0.354 ± 0.27	0.701 ± 0.96	1.349 ± 1.36







