

# FACTORS AFFECTING DIFFERENTIAL UNDERESTIMATES OF BIRD COLLISION FATALITIES AT ELECTRIC LINES: A CASE STUDY IN THE CANARY ISLANDS

## FACTORES QUE AFECTAN A LA SUBESTIMACIÓN DIFERENCIAL DE LAS COLISIONES DE AVES CON LÍNEAS ELÉCTRICAS: UN CASO DE ESTUDIO EN LAS ISLAS CANARIAS

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**SUMMARY.**—Carcass counts notably underestimate avian collision rates due to three main bias sources: imperfect detection, carcass removal by scavengers and carcass dispersion in unsearched areas. We assessed these sources of bias at electric lines of two Canary Islands, Lanzarote and Fuerteventura, quantifying the factors influencing them. We also carried out a cost-effectiveness assessment of carcass search done perpendicularly to electric line axis. We surveyed 230km of three types of electric lines (high-voltage, medium voltage and telephone lines) during three periods (July 2015, November-December 2015 and March 2016) searching for collision fatalities (N = 431), recording the species, the carcass distance from the electric line, mean cable height, carcass detection distance and decomposition state. In addition, we carried out a disappearance rate experiment to estimate carcass removal by scavengers. A generalised least squares model was used to analyse dispersion distance of carcass from electric lines, in relation to species body mass, mean cable height and line typology. Detection probability functions were fitted to estimate carcass detectability, incorporating body mass, decomposition state and habitat structure as covariates. A Generalised Mixed-Effects model was carried out to analyse carcass disappearance in relation to time elapsed since carcass placement, carcass size, season and island. Dispersion distance decreased with body mass and increased with cable height, being further

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at high-voltage lines. Overall, detection probability was 0.134, increasing with carcass size, decreasing with decomposition state and being lower in rocky areas which offered a significant challenge when walking through rough terrain. Disappearance rates differed between islands probably due to differences in avian scavenger abundance, increased with time elapsed and decreased with bird size. This study provides correction factors to obtain unbiased estimates of avian mortality rates within sparsely vegetated landscapes. Moreover, it identifies a 27m threshold distance at which the cost-effectiveness of searching for carcasses is optimised. —Gómez-Catasús, J., Carrascal, L.M., Moraleda, V., Colsa, J., Garcés, F. & Schuster, C. (2021). Factors affecting differential underestimates of bird collision fatalities at electric lines: a case study in the Canary Islands. *Ardeola*, 68: 71-94.

*Key words:* avian carcasses, Canary Islands, collisions at electric lines, cost-effectiveness assessment, decomposition rates, detectability, disappearance rates.

RESUMEN.—El conteo de cadáveres infravalora la tasa de colisión de aves debido a tres fuentes de sesgo: detección imperfecta, retirada de cadáveres por carroñeros y dispersión de cadáveres fuera de la zona de muestreo. En este trabajo se evalúan estas fuentes de sesgo en tendidos eléctricos de dos islas Canarias, Lanzarote y Fuerteventura, y se cuantifican los factores que les afectan. Además, se lleva a cabo un análisis de costo-efectividad en la búsqueda de cadáveres perpendicularmente al eje de los tendidos. Se muestrearon 230 km de tres tipos de tendidos eléctricos (alta tensión, media tensión y tendidos telefónicos) en tres temporadas (julio 2015, noviembre-diciembre 2015 y marzo 2016) y para cada colisión (N = 431) se identificó la especie y se registró la distancia del cadáver al tendido, altura media de los cables, distancia de detección del cadáver y el estado de degradación. Además, se llevó a cabo un experimento para estimar la tasa de desaparición por carroñeros. Se ajustó un modelo generalizado de mínimos cuadrados para analizar la distancia de dispersión de los cadáveres frente a la masa corporal, altura media de los cables y tipología de línea. En segundo lugar, se aplicaron funciones de detección para estimar la detectabilidad de los cadáveres incorporando la masa corporal, el grado de descomposición y la estructura del hábitat como covariables. Por último, se ajustó un modelo mixto generalizado para analizar la tasa de desaparición de cadáveres con relación al tiempo transcurrido desde la colocación del cadáver, su tamaño, la temporada y la isla. La distancia de dispersión disminuyó con la masa corporal e incrementó con la altura de los cables, siendo mayor en las líneas de alta tensión. La probabilidad de detección fue de 0,134, incrementándose con la masa corporal y disminuyendo con el estado de descomposición-degradación, y fue menor en zonas rocosas que imponen dificultades para caminar. La tasa de desaparición de cadáveres difirió entre islas debido probablemente a la abundancia de carroñeros, se incrementó con el tiempo y disminuyó con el tamaño corporal. Este trabajo proporciona factores de corrección para obtener estimas fiables de la tasa de mortalidad de aves en paisajes con escasa vegetación. Además, identifica una distancia umbral de 27 metros donde se alcanzan los valores máximos de coste-efectividad en la búsqueda de cadáveres. —Gómez-Catasús, J., Carrascal, L.M., Moraleda, V., Colsa, J., Garcés, F. y Schuster, C. (2021). Factores que afectan a la subestimación diferencial de las colisiones de aves con líneas eléctricas: un caso de estudio en las islas Canarias. *Ardeola*, 68: 71-94.

*Palabras clave:* cadáveres de aves, colisiones en líneas eléctricas, detectabilidad, índices de desaparición, índices de descomposición, islas Canarias, valoración de coste-efectividad.

## INTRODUCTION

Collision with man-made structures has been reported to be an important cause of avian mortality, which may have dramatic consequences at the population level (*e.g.*

Crivelli *et al.*, 1988; Bevanger, 1995; Hunt & Hunt, 2006; but see Arnold & Zink, 2011). Specifically, the increase in electricity demand over the last several decades has led to the expansion of electrical transmission grids, an important cause of avian mortality

through collision with electric lines (Drewitt & Langston, 2008; Ferrer, 2012; Bernardino *et al.*, 2018).

Estimates of avian collision rates with electric lines and other human infrastructures are commonly based on carcass counts (Stevens *et al.*, 2011). However, accurate quantification remains complex due to the existence of three major biases: i) imperfect detection (Ponce *et al.*, 2010; Stevens *et al.*, 2011); ii) carcass disappearance due to decomposition or removal by scavengers (Schutgens *et al.*, 2014; Costantini *et al.*, 2017); and iii) fall of carcasses outside the search zone (Huso & Dalthorp, 2014; Murphy *et al.*, 2016). These main bias sources affect the number of carcasses found by observers, which may notably underestimate bird fatality rates (Ponce *et al.*, 2010; Barrientos *et al.*, 2018). Therefore, correction factors should be applied to account for carcass count shortfalls due to sources of error during surveys and to provide unbiased estimates of bird mortality rates (Bevanger, 1999; Korner-Nievergelt *et al.*, 2011), for a proper estimation of human impact on bird biodiversity.

Understanding and quantifying the factors that influence bias sources is pivotal to obtaining accurate correction factors that may be site-, season- and/or species-dependent. Potential factors affecting detectability bias are carcass size (Ponce *et al.*, 2010; Borner *et al.*, 2017), habitat type (Stevens *et al.*, 2011; Schutgens *et al.*, 2014; Borner *et al.*, 2017), carcass age (*i.e.* decomposition state; Schutgens *et al.*, 2014) and differences in observer perceptual abilities (Ponce *et al.*, 2010; Borner *et al.*, 2017). Moreover, scavenger removal rate has been described to depend on carcass size (Ponce *et al.*, 2010; Schutgens *et al.*, 2014), season (Costantini *et al.*, 2017) and location (Ponce *et al.*, 2010; Stevens *et al.*, 2011; Costantini *et al.*, 2017; Borner *et al.*, 2017), the last of these probably due to site-specific factors such as geographical position relative to the distribution and abundance patterns of scavengers

(Kostecke *et al.*, 2001). Information on carcass dispersion patterns from the axis of electric lines is scarce, a matter that affects the definition of the searchable area and extrapolations to unsearched areas around the infrastructures (Huso & Dalthorp, 2014), especially considering the relationship of body mass to parabolic free-fall trajectories and the broad variation in the configuration and dimensions of electric lines (*e.g.* number of cables, tower heights). The particular characteristics of electric line infrastructures are highly dependent on line voltage (Miller, 1978), which may be expected to produce differences in carcass dispersion distance relative to the line axes.

Here we addressed the influence of imperfect detection, scavenger removal, carcass decomposition and carcass dispersion around overhead utility lines on the estimates of collision fatalities in sparsely vegetated semi-arid landscapes, considering three different types of utility lines (hereafter electric lines): high-voltage, medium voltage and telephone lines. Specifically, we quantified the bias sources and their underlying potential factors in order to obtain accurate correction factors. The aims were to: i) evaluate carcass dispersion patterns with respect to the axis of electric lines, examining the influence of species body mass, cable height and line typology on dispersal distances; ii) estimate carcass detectability, assessing the effect of bird size, decomposition state (*i.e.* carcass age) and habitat structure on the likelihood of carcass detection; and iii) measure carcass persistence in the field by carcass removal experiments, testing for the effects of time elapsed since carcass placement, carcass size, geographical position and season on carcass disappearance rates. Based on these results, we carried out an assessment of the cost-effectiveness of carcass search perpendicular to electric line axes in order to identify a threshold distance up to which survey efforts should be invested, enhancing the effectiveness of surveys.

There is no information available on carcass dispersion patterns with respect to the axes of electric lines. However, we expected that dispersal distances would be greater with small-sized carcasses and on electric lines with higher wires (*i.e.* high and medium-voltage lines) due to the influence of these factors on parabolic free-fall trajectories. On the other hand, in accordance with previous studies, we expected that carcass detectability would increase with carcass size (Borner *et al.*, 2017) and decrease with carcass age (*i.e.* decomposition state; Schutgens *et al.*, 2014), whereas detection probability would be greater in open habitats than in more vegetated ones (Arnett *et al.*, 2008; Smallwood, 2013). Moreover, carcass disappearance due to removal by scavengers was expected to be negatively related to carcass size, and to differ between seasons and sites due to differences in such specific factors as scavenger density and activity (Flint *et al.*, 2010; Henrich *et al.*, 2017). Lastly, carcass disappearance rates were predicted to increase as time since placement increased (Ponce *et al.*, 2010; Barrientos *et al.*, 2018).

## METHODS

### Study area

The study areas were on two eastern islands of the Canarian archipelago (Figure 1): Lanzarote (846km<sup>2</sup>, 670m a.s.l.; 29°2'6"N, 13°37'58.8"W) and Fuerteventura (1,660km<sup>2</sup>, 807m a.s.l.; 28°25'27"N, 14°0'11"W). The climate is semi-arid with mean temperatures ranging from 14°C to 29°C and annual precipitation below 200mm. The landscape is predominantly flat and semi-desertic dominated by xerophytic shrubs: *Launaea arborescens*, *Lycium intricatum*, *Salsola vermiculata*, *Suaeda* spp. and *Euphorbia* spp. Cultivated fields are interspersed by areas extensively grazed by goats (mainly in

Fuerteventura). The surveyed areas comprised a wide range of habitats, from lava fields to dunes. For more details on island characteristics see Fernández-Palacios & Martín-Esquivel (2001).

Three types of electric lines are present in both islands: i) high-voltage power lines (66 kV); ii) medium-voltage power lines (15-30 kV); and iii) telephone lines (< 1 kV). The voltage differences require differences in line typology. The number of cables or wires differs between power lines and telephone lines (ANOVA F-test,  $p < 0.0001$ ). High- and medium-voltage lines do not differ in cable number ( $p = 0.414$ ): of the surveyed infrastructures 99.45% of high-voltage lines have three cables and 0.55% have six cables, whereas 95.53% of medium-voltage lines have three cables and 4.47% have six cables. Telephone lines have significantly fewer cables than power lines ( $p < 0.0001$ ): 59.20% have one cable, 22.98% have two and 17.82% have three. The height of the lowest cable also differs between line types (ANOVA F-test,  $p < 0.0001$ ), being higher in high-voltage lines (mean  $\pm$  SD = 14.04  $\pm$  7.21m, 95% confidence interval -CI95% = 13.26-14.82m, N = 323), than in medium voltage lines (9.95  $\pm$  3.19m, CI95% = 9.15-10.75m, N = 61) and telephone lines (5.11  $\pm$  0.7m, CI95% = 4.87-5.34m, N = 37). Similarly the distance between the lowest and the highest cables differs between the three line types (ANOVA F-test,  $p < 0.0001$ ) being greater in high-voltage lines (7.15  $\pm$  2.87m, CI95% = 6.78-7.52m), than in medium-voltage lines (2.09  $\pm$  1.94m, CI95% = 1.53-2.66m) and telephone lines (0.22  $\pm$  0.52m, CI95% = 0-0.44m).

### Survey methodology

Electric lines were surveyed in three seasons of an annual cycle: July 2015, November-December 2015 and March 2016. In each

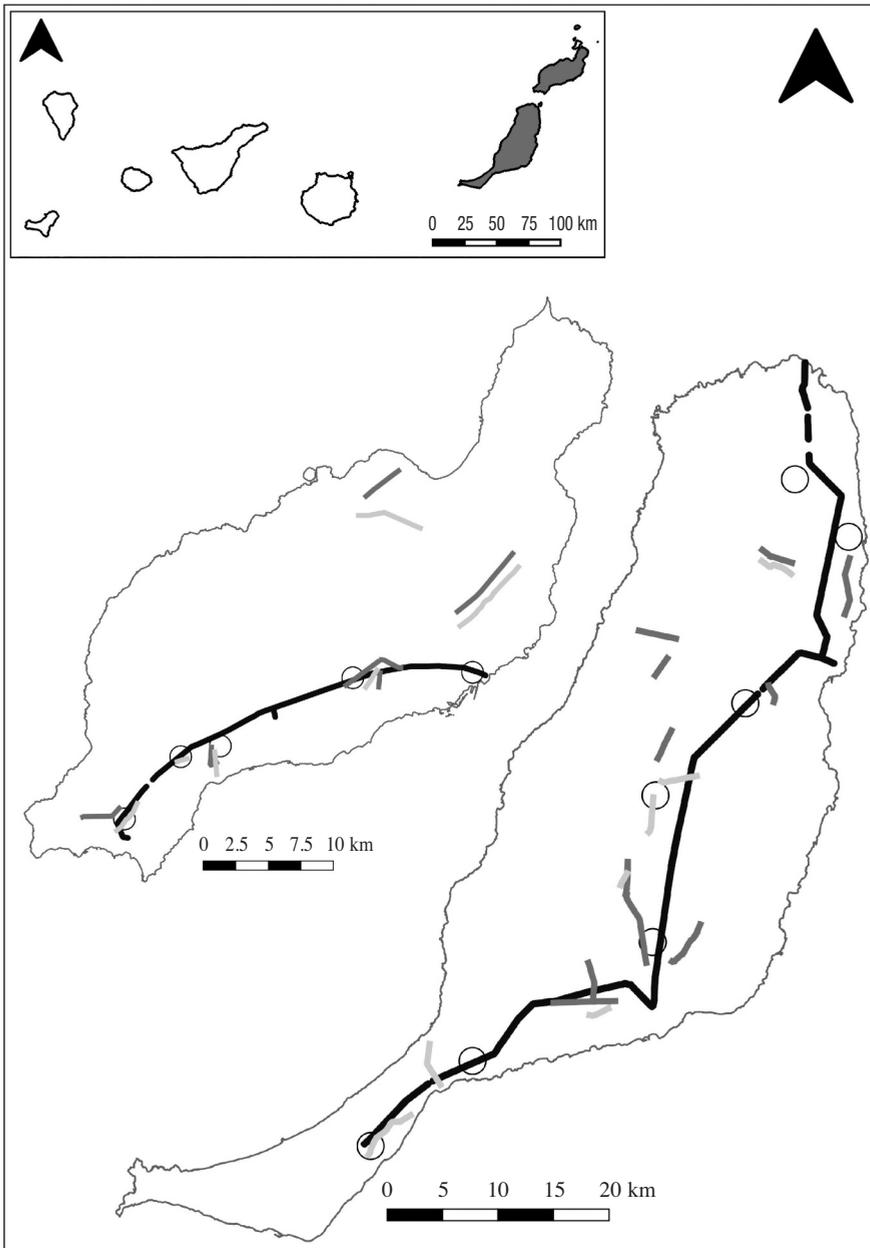


FIG. 1.—Eastern islands of the Canary archipelago: Lanzarote (top-left) and Fuerteventura (bottom-right) showing the high-voltage (black lines), medium-voltage (dark grey lines) and telephone (light grey lines) lines surveyed. Circles indicate the locations of the disappearance rate experiments.

[Islas orientales del archipiélago canario: Lanzarote (arriba a la izquierda) y Fuerteventura (abajo a la derecha). Se representan las líneas de alta tensión (líneas negras), media tensión (líneas en gris oscuro) y telefónicas (líneas en gris claro) muestreadas. Los círculos indican las localizaciones de los experimentos de la tasa de desaparición de cadáveres.]

sampling season, we surveyed 32.17km and 96.56km of high-voltage lines in Lanzarote and Fuerteventura, respectively (Figure 1). We also surveyed 20.39km and 40.40km of medium-voltage lines, and 18.16km and 22.40km of telephone lines, in Lanzarote and Fuerteventura respectively (Figure 1).

Electric lines were walked under similar favourable weather conditions that facilitate carcass detectability (*i.e.* absence of precipitations and fog), at a slow speed ( $3.39 \pm 0.43$ km/h) following a zig-zag pattern. The average length of the electric line stretches surveyed per person and day was 3.1km (from 0.4km up to 7.8km;  $N = 74$ ). Surveys were carried out by a total of nine different observers experienced in field and census work (six per study period). Two observers surveyed in parallel on each side of the high-voltage lines, whereas one observer surveyed medium-voltage and telephone lines keeping the electric line at the centre of the zig-zag transect (see Supplementary Material, Appendix 1). The average distance between the line and the furthest point from the line walked by the observer was 40.6m, *i.e.* the average width of the zig-zag pattern was 40.6m, giving a total length walked by the observer of 101.4m. The resulting zig-zagging index was  $1.67 \pm 0.22$  (see Supplementary Material, Appendix 1). High-voltage lines were surveyed up to 50m from the axis, whereas medium-voltage and telephone lines were surveyed up to 25m from the axis.

## Fatality records

A fatality record was defined as any remains of carcass consisting of at least a single bone or a set of five feathers, since fewer feathers may be due to causes other than mortality (*e.g.* moult, roost sites, fighting; Bevanger, 1999). Carcasses with clear evidence of other mortality causes (*e.g.* electrocution, predation by falcons) were excluded.

For each collision fatality event we recorded the following information: i) GPS coordinates; ii) date; iii) island; iv) species; v) distance from the electric line axis; vi) minimum and maximum cable height; vii) distance from the observer at which the carcass was first detected; and viii) decomposition state. Distance and height variables were visually estimated in the field after training. Five decomposition states were established *a priori*. State 1, or *fresh*, was characterised by the presence of soft tissues, ranging from recent death (less than 3-5 hours) to initial body inflammation due to bacterial action. State 2, or *emphysematous*, from showing very apparent inflammation to skin rupture due to internal gas pressure and superficial tissue decomposition. State 3, or *coliculative*, encompassed advanced decomposition and disappearance of soft tissues. During state 4, or *post-coliculative*, only dried tissues, cartilages and bones were present. Lastly, state 5, or *skeletal reduction*, referred to the mere occurrence of bone remains (see photographs of decomposition states in Supplementary Material, Appendix 1). Carcasses found in state 5 (*i.e.* skeletal reduction) were identified *ex situ* at the National Museum of Natural Sciences, using the natural history bone collections and digital pictures taken in the field alongside objects of known dimensions. Duplication of fatality records between sampling seasons was avoided by means of GPS location (average sampling for 1min to attain a precision of  $\pm 2$ m) and digital pictures of the remains and the surroundings.

Body masses were obtained from Perrins (1998; see Supplementary Material, Appendix 2, Table C1). Bird remains were classified according to initial body mass and their spread on the ground into three size categories that could easily accommodate well-known bird species: i) Small, for passerine-sized remains ( $< 20$ cm); ii) Medium, from Eurasian Collared-dove *Streptopelia decaocto* to Bulwer's Petrel *Bulweria bulwerii*

(20-35cm); iii) Large, from Eurasian Stone-curlew *Burhinus oedicnemus* to Cattle Egret *Bubulcus ibis* (35-55cm); and iv) Very large, for species or remains larger than Cattle Egret (> 55cm).

Habitat characteristics were measured within a 25m radius around each carcass in order to control for the influence of habitat structure and vegetation cover on carcass detection. The following variables were visually estimated in the field after previous training: i) five scores of soil typology (0 large rocks or lava fields, 1 stone/gravel soils, 2 compact soils, 3 sandy soils, 4 loose sandy soils and dunes; mean  $\pm$  SD:  $2.2 \pm 0.83$ ,  $N = 431$ ); ii) rock cover (mean  $\pm$  SD =  $24.8 \pm 31.4\%$ ); iii) cover of the herbaceous layer, including therophytes (mean  $\pm$  SD =  $13.5 \pm 21.7\%$ ); iv) shrub cover (mean  $\pm$  SD =  $5.2 \pm 8.5\%$ ); and v) mean shrub height (mean  $\pm$  SD =  $25.2 \pm 20.3$ cm).

### Disappearance rate experiment

We carried out an experiment with the aim of estimating the probability of carcass disappearance due to removal by scavengers or decomposition. A total of 90 and 72 carcasses were placed in July 2015 and March 2016, respectively. In July 2015, 45 carcasses were located at five sites in Lanzarote (nine carcasses per site) and at seven sites in Fuerteventura (six carcasses per site, with the exception of one site where nine were placed). In March 2016, a total of 30 and 42 carcasses were placed in Lanzarote and Fuerteventura, respectively (six carcasses per site; Figure 1). We placed two or three bird carcasses of each body-size class at each site, separated by at least 20m. The carcasses were chicks of Domestic Chicken *Gallus gallus domesticus* (small), Rock Pigeon *Columba livia* or Common Quail *Coturnix coturnix* (medium) and Domestic Chicken (large). We used these three groups in order to cover

the whole range of body sizes of the species found dead around electric lines on the two study islands. All carcasses were of recently dead animals. Carcasses were monitored on five occasions: 1, 3, 7, 15 and 30 days after placement in the field. Visits were more frequent at the beginning of the experiment due to expected higher disappearance rates soon after placement (e.g. Prosser *et al.*, 2008; Ponce *et al.*, 2010). Presence or absence of carcasses and the five decomposition states established beforehand were recorded on each visit. All remains were removed on the last monitored day.

Carcasses (kindly supplied by Oasis Park zoo, Fuerteventura) were provided frozen in order to avoid possible sources of error associated with carcass odour that could influence removal by scavengers. They were defrosted at ambient temperature the day before placement. Locations were selected near electric lines, spanning the habitat heterogeneity in their surroundings (Figure 1), since differences in vegetation structure and other environmental factors are expected to influence scavenger density and, therefore, disappearance rates (Bevanger, 1995). In order to avoid collision fatalities of attracted avian scavengers (e.g. Common Raven *Corvus corax canariensis*, Common Buzzard *Buteo buteo insularum*, Egyptian Vulture *Neophron percnopterus majorensis*) carcasses were placed near the studied electric lines but no closer than 100m. We georeferenced the location of each carcass with a portable GPS for subsequent revisions (with the average function during 1min for an enhanced spatial precision).

### Statistical analyses

#### *Carcass dispersion around electric lines*

The logarithmic distance of the fatalities from the electric line axis was analysed in

relation to species body mass, the average height of the wires at the location where the carcasses were found and the line typology (high-voltage, medium-voltage and telephone lines). A generalised least squares (GLS) model was fitted with the ‘nlme’ R package (Pinheiro *et al.*, 2019), taking into account heteroskedasticity-corrected standard errors and spatial auto-correlation of the location of carcasses. Spatial auto-correlation controls for type I error while establishing the right sample size for significance estimation; *i.e.* the distance from the electric line is expected to be correlated in nearby carcasses due to similarities in factors such as topography and habitat characteristics around them, prevailing wind exposure, hotspots of high mortality, etc. In this analysis, we employed all carcasses ( $N = 322$ ) found up to 25m from the axis of the three electric line types (*i.e.* high-voltage, medium-voltage and telephone lines), in order to account for the fact that the areas surveyed below telephone and medium-voltage lines were narrower.

We also carried out a cost-effectiveness assessment of carcass search from the axis of high-voltage lines. We focused on high-voltage lines due to the larger sample of carcasses recorded there and the broader area sampled (up to 50m). The sampling effort invested at a particular distance from the axis was equated to the proportion of area covered up to the distance at which the high-voltage lines were surveyed (see “Surveying methodology” above). For instance, the proportion of the area covered up to 30m was  $0.6 = 30/50$ . Thus, sampling proportion increased linearly with the distance from the axis of the high-voltage lines. The cost-effectiveness of carcass search along the distance gradient to the axis was calculated as the difference between the cumulative proportion of carcasses and the proportion of area covered up to a particular distance.

Considering the dispersion pattern of carcasses around the axis of the high-voltage

power lines, and their detectability patterns when searched for, it is possible to ascertain the theoretical proportions of carcasses detected from those available in the field for one, two or three observers walking parallel to the axis of the power line. This simulation approach was carried out considering (i) one observer walking alone below the line axis, (ii) two observers walking at 13m to either side of the line axis, and (iii) as (ii) but with a third observer walking along the axis itself. The R script for carrying out the simulations for remains of large and very large species is presented in the Supplementary Material, Appendix 3. In a first step we simulated the half-normal distribution of carcasses according to the pattern shown in Figure 2, within 1m distance intervals from the line axis up to 50m. In a second step we simulated the probability of detection of large/very large remains according to the information in panels C and D of Figure 3. Combining those two distributions, it is possible to estimate the proportion of carcasses detected from a previously established distance, considering those available according to their distances from the power line axis (*i.e.* proportion of carcasses detected in each 1m distance interval = number of carcasses within that distance interval  $\times$  probability of detection considering the distance of the observer from that point). Finally we estimated the proportion of carcasses detected from those available within each 1m distance interval for each observer in each of the three sampling scenarios. This procedure was also applied to small bird remains/species, according to data in panel A of Figure 3.

### *Carcass detectability*

We used distance sampling methodology (Buckland, 2007), fitting detection functions to estimate carcass detectability using the ‘Distance’ R package (Miller, 2017). All de-

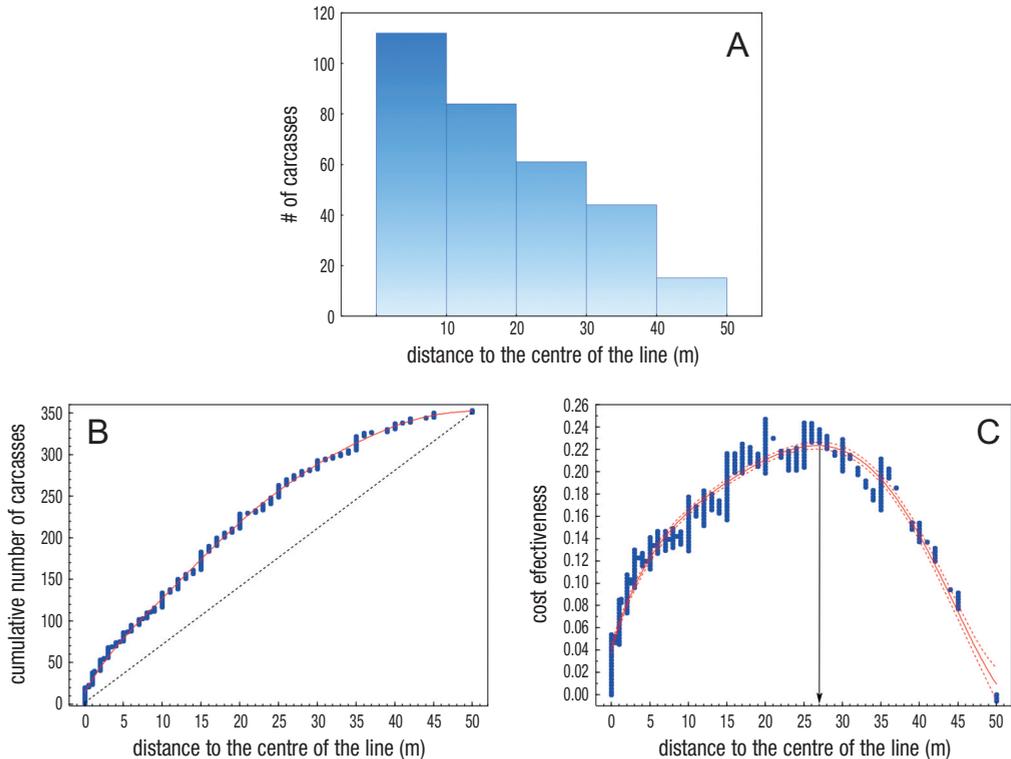


FIG. 2.—Distribution of (A) the dispersion distances of carcasses and (B) the cumulative number of carcasses up to 50m from line axis, and (C) the cost-effectiveness of sampling while using a zig-zag walking pattern (see Supplementary Material, Appendix 1). Only data for high-voltage lines is presented ( $N = 353$  different carcasses found along 128.7km of electric lines searched on three occasions –July, November, March–). The fitted curve in panel (B) has been obtained by means of a cubic polynomial smoothing, while the dashed straight line indicates the cumulative proportion of carcasses on an expectation of an “equal benefit” search survey. The cost-effectiveness pattern in panel (C) was estimated as the difference between the continuous curve and the dashed line in panel (B), expressed as a proportion of carcasses found; the fitted curve was estimated by means of quintic polynomial smoothing (with its 95% confidence interval; dashed lines). The vertical arrow in panel (C) shows the distance from the electric line axis at which the cost-effectiveness search for carcasses is maximised.

[Distribución de (A) las distancias de dispersión de los cadáveres, (B) el número acumulado de cadáveres hasta los 50m de distancia al eje del tendido, y (C) la relación esfuerzo/eficacia de muestreo con un patrón de muestreo en zig-zag (véase en el Material Suplementario, Apéndice 1). Sólo se representan los datos para las líneas de alta tensión ( $N = 353$  cadáveres diferentes encontrados en 128,7 km de líneas eléctricas muestreadas en tres ocasiones –Julio, Noviembre, Marzo–). La curva ajustada en el panel (B) se ha obtenido mediante un suavizado polinómico cúbico, mientras que la línea recta y discontinua indica la proporción acumulada de cadáveres sobre una expectativa de una “igualdad de beneficio” por esfuerzo de prospección. El patrón de esfuerzo/eficacia en el panel (C) fue estimado como la diferencia entre la curva continua y la línea discontinua en el panel (B), expresado como la proporción de cadáveres encontrados; la curva ajustada se ha estimado mediante un suavizado polinómico de orden cinco (con el intervalo de confianza al 95%; líneas discontinuas). La línea vertical en el panel (C) muestra la distancia desde el eje de la línea eléctrica a la que se maximiza la relación eficacia/esfuerzo en la búsqueda de cadáveres.]

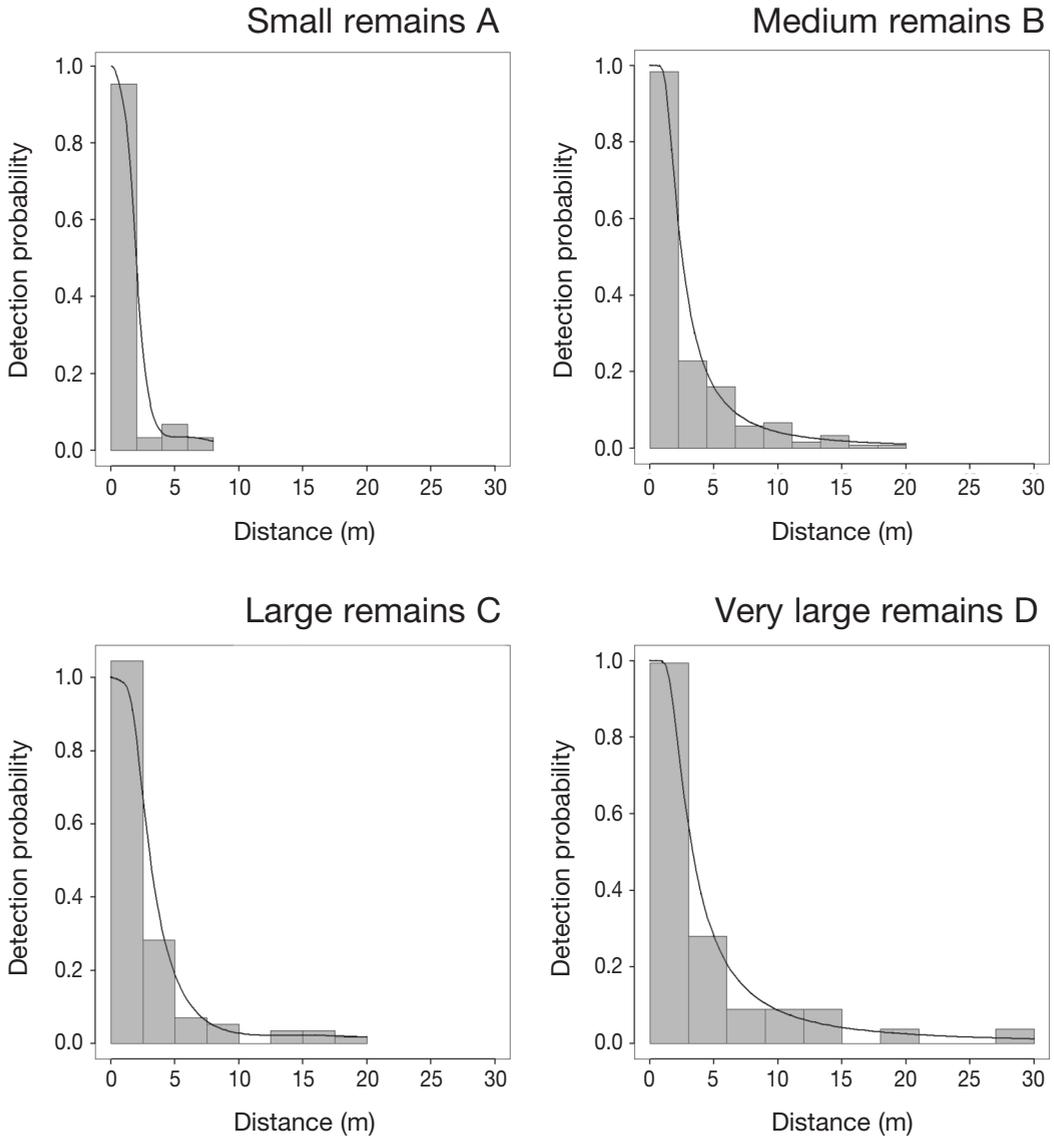


FIG. 3.—Distances from the observer to the carcasses considering four size categories in accordance with species body mass and the size of the remains. Curved lines depict the probability of detection models using hazard-rate distributions with cosine adjustments. The four size classes are (A) small ( $N = 32$ ), (B) medium ( $N = 185$ ), (C) large ( $N = 127$ ), and (D) very large ( $N = 87$ ). See methods for description of these size categories.

[Distancias de detección de los cadáveres medidas desde el observador, considerando cuatro categorías de tamaño que consideran globalmente la masa corporal de las especies y el tamaño de los restos encontrados. Las curvas representan los modelos de probabilidad de detección “hazard-rate” (tasa de riesgo) con ajuste coseno. Las cuatro categorías de tamaño son (A) pequeño ( $N = 32$ ), (B) mediano ( $N = 185$ ), (C) grande ( $N = 127$ ), y (D) muy grande ( $N = 87$ ). Véanse los métodos para una descripción de estas categorías de tamaño.]

tection distances were considered in an initial analysis to estimate the overall detection probability, because a detectability model incorporating the uncertainty linked to the observer's skills and perceptive abilities did not improve the model (*i.e.* the model including the observer as a nominal factor had a larger AICc figure and was not significant). We applied half-normal and hazard-rate canonical detection functions with cosine adjustments (cosine adjustment terms were automatically selected according to AIC figures obtained while carrying out the distance models) to the distribution of distances obtained for 431 different carcasses found under all electric line types. This first model included different covariates that can affect the probability of detection: species-specific body mass of each carcass, an ordered factor defining the state of decomposition of carcasses using five levels (from 1: fresh whole animal, to 5: degraded and fragmented remains), and three PCA components summarising the habitat structure around the remains (see below). These covariates were z-standardised (*i.e.* mean 0 and standard deviation 1) prior to data analysis in order to obtain standardised beta regression coefficients. The best model (*i.e.* half-normal or hazard-rate distributions) was selected according to the Akaike Information Criterion (AIC).

Because the probability of detection of bird remains was significantly affected by body mass in the previous analysis (see Results), we estimated the probability of detection of carcasses for each of the four size classes (*i.e.* small, medium, large and very large) using the hazard-rate distribution with cosine adjustments. We used the maximum observed distance as the right truncation considering the good GOF statistics and the lack of outliers distant from the observer. The Effective Strip Width (ESW) while searching for bird carcasses was separately

calculated for each body-size class of bird remains (*i.e.* multiplying the maximum distance threshold by the probability of detection up to that distance).

We carried out a Principal Component Analysis (PCA) with the variables describing the habitat structure at the locations where carcasses were found in order to reduce variable redundancy and habitat dimensionality. We used the varimax rotation of the initial factorial solution to ease the interpretation of the factors obtained, retaining those components with eigenvalues > 1. We employed the 'psych' and 'GPArotation' (Bernaards & Jennrich, 2005) R packages. The first component (PC1) accounted for 28% of the variance and was associated with the development of the shrub layer (factor loadings: shrub cover = 0.89, shrub height = 0.74). The second component (PC2) defined a soil gradient from rocks to sand (factor loading = 0.65) versus the development of the herbaceous layer (-0.87), accounting for 24% of the variation in habitat structure. Finally, the third component (PC3; 25% of variance) was positively associated with the cover of stones and rocks (factor loading = 0.90).

### *Carcass disappearance*

Carcass disappearance was analysed by means of a split-plot design using Generalised Mixed Effects models, including the site as a random effect. Season (July and March) and time since carcass placement in the field (1, 3, 7, 15, 30 days after placement) were incorporated as within-subjects fixed factors. Lastly, carcass size (small, medium and large) and island (Lanzarote and Fuerteventura) were incorporated as between-subjects fixed effects. The response variable was the proportion of carcasses for each size class remaining per site at each sampling visit (*i.e.* binomial distribution). That is to say, the sam-

ple unit for data analyses was the size class at each different site per island, recording the persistence of the two or three carcasses per size class on five different occasions and in two seasons.

We fitted three models with the same random structure but different fixed structure: 1) null model, without fixed effects; 2) main effects model, incorporating three fixed factors (island: Fuerteventura vs. Lanzarote; season: July vs. March; carcass size: small, medium and large) and time elapsed since carcass placement as fixed covariate (in logarithm, since a decelerated positive effect on the disappearance of carcasses was expected; Ponce *et al.*, 2010); and 3) the main effects model plus all two-way interactions including carcass size, since the full saturated four-way model was not possible due to sample size limitations. Akaike's second-order information criterion corrected for small sample sizes (AICc) was employed to select the best model. The significance of interaction terms was estimated using the equivalent type II SS applied to maximum likelihood models. We used the 'lme4', 'lmerTest' and 'pbkrtest' R-packages (Bates *et al.*, 2019) to fit Generalised Mixed Effects models.

## RESULTS

A total of 431 carcasses was found in the field, 257 in Fuerteventura and 174 in Lanzarote. In both islands the greater number of carcasses was found during the third sampling period in March 2016 (124 and 67 carcasses in Fuerteventura and Lanzarote, respectively), followed by the second in November-December 2016 (71 and 62 carcasses, respectively) and the first in July 2015 (62 and 45 carcasses, respectively). Carcasses were assigned to 22 different bird species; 23 carcasses that were unidentifiable were assigned to a size class (see Supplementary Material, Appendix 2, Table C2).

### *Carcass dispersion around electric lines*

The GLS model was highly significant (likelihood ratio test:  $\chi^2 = 22.71$ ,  $df = 4$ ,  $p < 0.0001$ ; pseudo  $R^2 = 7.5\%$ ). Body mass of birds was negatively related to the distance from wires at which the carcasses were found (partial standardised regression coefficient  $\beta = -0.16$ ,  $p < 0.01$ ). Conversely, the average height of wires was positively related to the dispersion distance ( $\beta = 0.12$ ,  $p = 0.017$ ). The factor line typology had no significant effect on dispersion distance ( $p = 0.876$ ).

The dispersion of the carcasses with respect to the axis of electric lines followed a half-normal distribution. Figure 2A shows the pattern found below high-voltage lines surveyed up to 50m from the axis (323 different carcasses detected along 128.7km of electric lines sampled in three different seasons). Thirty-four percent of the carcasses were found at less than 10m from the electric line axis. This proportion reached 50% (*i.e.* quantile 0.5) up to 16m distance from the line axis, 75% of carcasses up to 27.5m, 90% up to 36m, and 95% up to 42m. Summarising, despite the effort of searching for carcasses up to 50m from the line axis, only 20% of bird collision deaths were detected beyond 30m, despite the area from 30 to 50m receiving 40% ( $20/50 \times 100$ ) of the sampling effort with respect to the total area covered. The difference between the proportion of carcasses found from the axis of the electric line up to a certain distance and the area covered are shown in Figures 2B and 2C. The cost effectiveness of searching for carcasses reaches its maximum at 27m from the axis of electric lines, for electric lines with three to four wires and an average height of 16.2m (95% confidence interval: 5-39m). As many as 74% of the carcasses were found within 27m of the electric lines, despite requiring only 54% ( $27/50 \times 100$ ) of the time and effort of sampling up to 50m.

### Carcass detectability

The maximum distances at which the carcasses were detected in the field ranged from 8m for the small class (S) to 30m for the very large class (VL), with maximum values of 20m for the medium (M) and large (L) classes.

The most parsimonious model was the hazard-rate with cosine adjustments of order 2 (AIC = 1872.6), followed by the half-normal model with cosine adjustments of order 2 and 4 (AIC = 1917.9). Thus, only the results of the hazard-rate model are presented below. The Cramer-von Mises test of goodness-of-fit indicates a good fit of the hazard-rate model to the data (C-vM statistic = 0.25,  $p = 0.193$ ).

The overall detection probability (controlling for the five covariates included in the model) was 0.134 (95% confidence interval: 0.118-0.150). Therefore, only 13.4% of the carcasses under the electric lines were detected up to 30m from the observer (*i.e.* the maximum distance at which the carcasses were detected in the field), showing that only

a small proportion of dead bird remains (approximately one eighth) are detected while surveying the lines for carcasses. The probability of detection of bird remains was significantly affected by the body mass ( $p < 0.0001$ ) of each species and by the state of decomposition ( $p < 0.0001$ ), with a larger magnitude for the second effect according to standardised partial regression coefficients ( $\beta$ ). Larger bird species had a higher probability of detection ( $\beta = 0.19$ ), and this probability sharply decreased as the decomposition-fragmentation state of the carcasses increased ( $\beta = -0.35$ ). Considering the three components of habitat structure around the carcass locations, only that related to rock cover (bedrock or stones larger than a tennis ball; PC3) was significantly related to the probability of detection ( $p < 0.01$ ,  $\beta = -0.151$ ): this decreased as rock cover increased. The results regarding how body mass and the decomposition-fragmentation state of carcasses affect the probability of detection suggest breaking down the detectability according to groups of “relative size” of bird remains,

TABLE 1

Decomposition-fragmentation state of carcasses found in the field (1-fresh, 2-emphysematous, 3-coliculative, 4-post-coliculative, 5-skeletal reduction) according to initial species body mass. Results are expressed in percentages with respect to the total number of carcasses in each body mass class (N).

[Estado de descomposición-fragmentación de los cadáveres encontrados en el campo (1-fresco, 2-enfismatoso, 3-colicuativo, 4-post-colicuativo, 5-reducción esquelética) atendiendo a la masa corporal de las especies. Los resultados se expresan en porcentajes con respecto al total del número de cadáveres en cada una de las clases de masa corporal (N).]

BODY MASS	Decomposition-fragmentation score					N
	1	2	3	4	5	
< 100 g	12.5	18.8	12.5	31.3	25.0	16
100-250 g	7.5	3.7	12.4	17.4	59.0	161
250-1000 g	2.6	0.5	3.6	11.3	82.1	195
> 1000 g	5.1	0.0	6.8	15.3	72.9	59

taking into account the original size of the bird and to what extent it has been broken down by decomposition and fragmentation. Table 1 shows the relationship between four classes of species body mass and the five levels of decomposition-fragmentation of the 431 different carcasses found in the field.

The probability of detection, as well as the Effective Strip Widths (ESW) while searching for bird carcasses are presented in Table 2 separately for four different sizes of bird remains. In addition, the distributions of detection distances are shown for each size class in Figure 3.

### *Carcass disappearance*

The best model was the main effects model plus all two-way interactions including carcass size (AICc = 445.4; main effects model, AICc = 455.1; null model, AICc = 936.4). This model was highly significant (LRTest:  $\chi^2 = 518.4$ ,  $df = 13$ ,  $p < 0.0001$ ), accounting for 81.4% of the variation in carcass disappearance rates. The persistence rate of carcasses was higher ( $p = 0.044$ ) in Lanzarote (adjusted mean = 0.877) than in Fuerteventura (0.520). Season had a negligible effect on carcass disappearance ( $p = 0.640$ ). Finally,

TABLE 2

Models fitted to the detection distances of four different size classes of bird remains: small (for passerine-sized remains, < 20cm; N = 32), medium (20-35cm remains; N = 185), large (35-55cm remains; N = 127) and very large (> 55cm remains; N = 87; see Methods and Figure 3). Detection distances for each size class have been truncated at maximum distance figures. Detectability models were built for each size of carcasses considering hazard-rate distribution, with cosine adjustments. The detection probability (Pdetec) and the standard error (se) at the maximum distance at which the carcasses were detected (Dmax in m) are provided for each size class. ESW is the effective strip width (expressed in m). All Cramer-von Mises goodness of fit tests, which measure the difference between the empirical distribution and the probability distribution function in a quantile-quantile plot, were not significant after the false discovery rate adjustment for multiple P estimations ( $P > 0.104$ ).

[Modelos de detectabilidad ajustados a las distancias de detección de las cuatro clases de tamaño para los restos de aves: pequeños (restos con tamaños similares al de un paseriforme, < 20 cm; N = 32), medianos (restos de 20-35cm; N = 185), grandes (restos de 35-55 cm; N = 127) y muy grandes (restos > 55 cm; N = 87; véase Métodos y Figura 3). Las distancias de detección para cada tamaño han sido truncadas a la distancia máxima. Los modelos fueron construidos para cada tamaño usando modelos de "hazard-rate" (tasa de riesgo) con ajuste coseno. Se presenta para cada clase de tamaño la probabilidad de detección (Pdetec) y el error estándar (se) desde 0 m hasta la distancia máxima a la que los cadáveres fueron detectados (Dmax en m). ESW se refiere al ancho de banda efectivo (expresado en m). Los tests de bondad de ajuste de Cramer-von Mises, los cuales miden la diferencia entre la distribución empírica y la función de distribución en un gráfico cuantil-cuantil, no fueron significativos después de haber controlado por las múltiples estimaciones de P mediante el método fdr (false discovery rate;  $P > 0,104$ ).]

Size class	Dmax (m)	Pdetec ± se	ESW (m)
Small	8	0.314 ± 0.059	2.5
Medium	20	0.180 ± 0.018	3.6
Large	20	0.197 ± 0.027	3.9
Very large	30	0.166 ± 0.022	5.0

bird size and time elapsed had a paramount influence on carcass disappearance ( $p < 0.0001$ ). The interaction term island by size was not significant ( $p = 0.952$ ). The effect of body size was marginally different across seasons ( $p = 0.058$ ), with a higher disappearance rate of large birds in July (0.948) than in March (0.990), with no clear changes in the other two sizes. The effect of time elapsed since carcass placement in the field changed among body size classes ( $p = 0.001$ ; see Figure 4): persistence rate decreased more abruptly for small birds.

## DISCUSSION

This work provides important insights on bias sources when estimating avian collision

rates with electric lines, derived from carcass counts in arid landscapes characterised by low vegetation cover. Imperfect detection and carcass removal by scavengers are the two major bias sources affecting carcass counts (see also Ponce *et al.*, 2010; Borner *et al.*, 2017; Barrientos *et al.*, 2018). To our knowledge, this is the first study addressing the factors affecting the dispersion patterns of carcasses around electric lines, defining a methodological and analytical approach for establishing the sampling areas around such lines.

The methodology employed in this study would have certain limitations if the main aim were to obtain accurate mortality estimates. Firstly, three visits in nine months is less desirable to obtain absolute estimations of bird fatalities than one visit every week or fortnight (but see Shaw *et al.*, 2018 for a

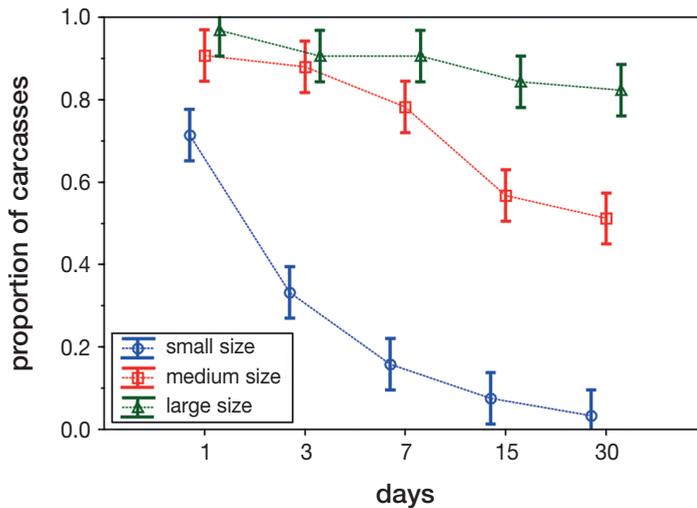


FIG. 4.—Proportion of carcasses of small (chicks of Domestic Chicken), medium (Rock Pigeons or Common Quails) and large (Domestic Chicken) birds remaining 1, 3, 7, 15 and 30 days after they were placed in the field. Sample size is two birds per size class at 12 different localities and on two different occasions (July 2015 and March 2016). Vertical bars are mean  $\pm$  standard error.

[Proporción de cadáveres de aves pequeñas (pollos de gallina doméstica), medianas (paloma bravía o codorniz común) y grandes (gallina doméstica) que permanecieron después de 1, 3, 7, 15 y 30 días de exposición en el campo. El tamaño de muestra es de dos aves por categoría de tamaño en 12 localizaciones distintas y en dos ocasiones diferentes (julio 2015 y marzo 2016). Las barras verticales representan la media  $\pm$  error estándar.]

similar approach with four sampling periods for a whole annual cycle). Nevertheless, under logistic, funding or time constraints the only possibility is to deal with sources of sampling biases, to model them and to apply that knowledge to the data recorded in the field at lower frequencies. Secondly, without clearing the remains before the first survey it is difficult to estimate the time from collision and thus, the number of casualties per unit of time. Fieldwork should respect the legal regulations related to the manipulation of bird remains, as many of them are species of conservation concern. In many instances, the researchers cannot wait until the environmental rangers walk all the surveyed power lines to confirm and remove all carcasses whose spatial locations were provided by the research team. Moreover, to clear the area below electric lines of carcasses prior to sampling requires a great deal of effort that the funding of a research project probably could not afford, especially under extensive monitoring programmes (e.g. we walked 531km over 262 hours per study period searching for carcasses). The impossibility of clearing the areas under the power lines of carcasses demands a concurrent methodological approach dealing with the temporal variation in the disappearance and decomposition state of the bird fatalities, and obtaining detailed information of those “historical records” by means of measuring their degradation state, photographing the remains and obtaining accurate GPS positions. Thus, during the second sampling session, the researchers could check if they have found the same carcasses by considering the spatial locations and photos taken on the first occasion. By means of this approach we were able to infer with sufficient precision whether bird fatalities had occurred during the previous 30 days (degradation state lower than 4; Moraleda *et al.*, in prep.), and thus we could restrict the sample of bird fatalities only to the last week, fortnight or month. Therefore, although more

effort-demanding sampling protocols are recommended and should be prioritised if resources are available to obtain accurate, absolute, mortality estimates, disappearance rate and decomposition experiments should be conducted in order to determine correction figures and not to underestimate bird fatalities.

#### *Carcass dispersion around electric lines*

Dispersion patterns of carcasses after colliding with human structures is key to defining the shape and extension of the searchable area during carcass counts (Huso & Dalthorp, 2014), essential to extrapolate fatality estimates for unsearched areas accurately. These aspects have received considerable attention at other human structures (e.g. wind farms; Hull & Muir, 2010; Huso & Dalthorp, 2014) but not with fatalities associated to electric lines. Our results suggest that dispersion patterns of carcasses around electric lines depend on species size and the height of the cables, a key difference between line typologies (see ‘*Study area*’ in Methods). Firstly, cable height was the most important predictor, positively affecting dispersion distance. This means that taller electric lines demand broader search areas, and thus the sampling belt should be defined according to the height of the electric line. Secondly, the dispersion distance of carcasses was negatively affected by body mass suggesting that large birds are more likely to be found near the line than small birds. This result contrasts with the effect found at wind turbines where larger birds tend to fall further away (e.g. Hull & Muir, 2010). This discrepancy may be related to the different nature of the collisions: impact with static cables *v.* the force exerted by the blades of wind turbines.

The evaluation of dispersion patterns of carcasses along with a cost-effectiveness assessment of carcass search, can be employed to

optimise the methodologies for estimating collision fatality rates. This approach allowed us to identify a 27m distance threshold at which the cost effectiveness of searching for carcasses reached its maximum. Beyond this distance, the proportion of carcasses found decreased relative to the investment of physical effort. However, this result is contingent on the type of infrastructures, habitats and species involved, and the 27m threshold should not be generalised to other study areas. Only 26% of bird collision deaths were detected > 27m from the axis of the studied electric lines, in spite of the fact that 46% of the time and physical effort was invested in sampling from 27 to 50m. This suggests that, even for high-voltage lines, it is unprofitable to sample beyond 27m from the axis, considering time-effort costs and the amount of bird fatalities recorded for a broad spectrum of avian species from Lesser Short-toed Lark *Calandrella rufescens* to Houbara Bustard *Chlamydotis undulata*. However, a drawback of the narrowing of the sampling belt is that a proportion of small-sized birds may not be detected (20.3% of birds smaller than 250g). Future studies addressing avian mortality rates at high-voltage lines should take into account this 30m distance threshold, in order to optimise sampling effort. However, these results are dependent on other sources of bias not considered in this study that may influence carcass dispersion patterns. For instance, injured birds may move further from the electric line axis outside the search area (*i.e.* crippling bias, Heijnis, 1980; Bech *et al.*, 2012; Murphy *et al.*, 2016). In addition, stochastic events such as wind direction at the moment of collision or carcass displacement by scavengers may affect recorded fall distances. Even though these factors were affecting the dispersion data of our study, they were not included in the analysis as predictor variables, thus contributing to the low amount of deviance accounted for by the generalised model (pseudo  $R^2 = 7.5\%$ ).

### *Carcass detectability*

Previous studies have highlighted the low detectability of body remains during carcass searches, leading to the underestimation of bird mortality rates at electric lines and other infrastructures (*e.g.* communication towers, fences, roads; Stevens *et al.*, 2011; Santos *et al.*, 2016; Barrientos *et al.*, 2018). Differences in detection rates have been attributed to site- (Stevens *et al.*, 2011; Smallwood, 2013) and species-specific factors (Smallwood, 2007; Ponce *et al.*, 2010; Barrientos *et al.*, 2018). In our study, the overall detection probability was 0.134, which means that *c.* 86.6% of carcasses were passed undetected up to 30m from the observer. Moreover, detection probability values sharply decreased as the decomposition-fragmentation state increased. These results suggest a joint effect between body mass and decomposition state, since for instance, a large bird such as a Common Raven may be less detectable several months after collision than a recent fatality of a smaller bird, such as a Eurasian Collared-dove. On the other hand, the probability of detection is also habitat-dependent, being lower in very rocky areas but unaffected by vegetation cover. Some studies have attributed the effect of vegetation cover to a loss in visibility (Stevens *et al.*, 2011; Smallwood, 2013) but others did not find any effect of habitat structure on detection probabilities (Ponce *et al.*, 2010; Borner *et al.*, 2017). Our study area is dominated by sparsely vegetated landscapes with an expected low influence on the detection probability of bird remains. Nevertheless, rock cover offered a significant challenge when walking through rough terrain. Rocky (*e.g.* malpaíses) or stony (*e.g.* large loose stones close together) soils demand continuous attention so as not to fall and get hurt while searching for bird carcasses. This is especially important in hillside areas with steep slopes and deep runoff cracks. In fact, all the people involved in this study have

fallen on several occasions, resulting in superficial wounds and bruises, or damage to clothing or equipment. Therefore, focusing attention on foot placement while walking would reduce the probability of detection of carcasses, especially those located at greater distances. Future surveys should consider locomotion difficulties associated with terrain, a usually neglected habitat bias on detection probabilities while searching for fatalities along electric lines or other infrastructures.

Results of probability detection models are useful to define an effective strip width while searching for bird carcasses and to establish the proportion of the area sampled below the electric lines. According to our results on ESW (Table 2), if the goal were to sample very large bird remains up to 50m from a high-voltage line, two observers walking in parallel for 1km separated by 25m from the axis would efficiently cover two ESW belts = 5m to either side of the census line per person, or 20,000m<sup>2</sup> (*i.e.* 2 sides of the census line per observer × 5m of ESW × 2 observers × 1000m). This is only a small fraction of the total area to be covered (*i.e.* 50m × 2 sides of the electric line × 1000m = 100,000m<sup>2</sup>): 20,000m<sup>2</sup> out of 100,000m<sup>2</sup>, or 20%. This figure is even lower if the goal were to quantify fatalities of small birds: only 10% of the area to be covered would be sampled efficiently (*i.e.* 2.5m of effective strip width).

The placement of fresh carcasses of large birds in the field (*e.g.* Domestic Chickens) and the subsequent search for those carcasses by other observers who do not know their location has been proposed as a shortcut to estimate the detection probability of bird remains (*e.g.* Ponce *et al.*, 2010). However, detectability values obtained from these conventional trials are suitable in specific carcass samplings where electric lines are initially walked in order to clear any existing remains, so that the carcasses found during surveys a few days later (*e.g.* seven days after

the initial clearing visit) are fresh and show low variation in decomposition-disintegration state. Nevertheless, the carcasses found with that sampling protocol only involve a very short time-span that would have to be extrapolated to a long, non-sampled, period of time, or should be repeated on a weekly or monthly basis. This surveying methodology is highly demanding from a financial and logistical point of view or impractical when hundreds of kilometres have to be covered. In this scenario, we suggest the distance sampling method as a complementary approach for the following reasons. Firstly, the remains detected in the field without clearing previous remains show a variation in decomposition-disintegration state impossible to simulate with conventional detectability trials. Probability of detection is a function of the size of bird remains and thus the whole body of, for example, a recently dead Common Raven is considerably more detectable than the wing bones of three-month old remains of the same species. Secondly, the tests of the probability of encountering previously located carcasses in the field are carried out over relatively short distances (*e.g.* 2-4km transects) and participants are sometimes told that a test of their perceptual abilities will be carried out. This “exam” situation intensifies attention over short periods of time and might maximise the probability of detection under a search situation that is not equivalent to other more routine and prolonged sampling procedures. Therefore, it is highly likely that carcass encounter tests actually measure the maximum probabilities of detection, rather than the average probabilities that more closely reflect the circumstances of longer sampling procedures, that may involve walking difficulties and mental and physical fatigue, for example. In fact, these differences between methodologies may explain the lower average detectability value obtained in this study compared with previous studies based on conventional carcass detectability

trials (13.4% vs 25-71%, Ponce *et al.*, 2010; Stevens *et al.*, 2011). Finally, the methods for estimating detection probability by noting the distance at which objects are detected are very refined and have robust statistical support (Buckland, 2007). We suggest such methods may be superior to simply “sowing” and subsequent searching for fresh bird carcasses, that do not represent all the environmental, taxonomic and decomposition state variability found under true sampling conditions.

#### *Line transects planning and proportion of carcasses detected*

Figure 5 illustrates the variation in the percentage of large bird carcasses detected (*i.e.* larger than a Eurasian Stone-curlew *Burhinus oedicnemus* > 35 cm), by one, two or three researchers. Only 42.6% of the available carcasses are detected with one observer walking below the axis of the electric line (Figure 5A). This percentage increases to 68.0% with two observers walking in parallel at 13m from the electric line axis (Figure 5B). There is a slight decrease in the proportion of large and very large carcasses detected at the line axis (*i.e.* 0m) as a consequence of the separation of the observers, considering the probability of detection curves of large and very large carcasses (see Figure 3C-3D). If three observers work together in the search of carcasses, one below the line axis and the other two walking in parallel 22m to either side of the line, they find 82.2% of the available carcasses (Figure 5C). The previous distances of separation from the axis of the high-voltage power lines are those that maximise the proportion of carcasses detected. If the analysis is repeated for small birds (*i.e.* mainly passerines < 100g and < 20cm in length) the percentage of detected carcasses with only one observer walking below the axis of the high-voltage power line is 9.8%, 18.8% for

two observers walking in parallel 4m from the axis, and 27.2% for three observers (one below the electric line, and one 8m to either side of the axis). The optimal separation from the line axis for two or three observers involved in the search of carcasses is well below of the cost-effective distance of *c.* 30m shown in Figure 2. The total proportions of carcasses of small and large birds found at other separation distances from the line axis are presented in Figure 5D.

There is a diminishing return in the number of carcasses detected per person as the number of observers increases. Only a few carcasses of large birds pass unnoticed when three observers walk in parallel separated by 22m (18%), increasing to *c.* 40% when only one observer below the axis of the electric line is involved. In other words, tripling sampling effort only results in an increase of *c.* 20% in the detection of large bird carcasses. Thus, environmental managers should balance the costs of sampling effort in relation to number of carcasses found according to the degree of conservation concern of the species under study.

#### *Carcass disappearance*

Carcass removal by scavengers has been described as another important bias source affecting estimates of avian mortality rates due to collisions (Farfán *et al.*, 2017). The effects of time elapsed since collision and carcass size on disappearance rates have previously been highlighted (Ponce *et al.*, 2010; Schutgens *et al.*, 2014). Our results markedly support previous research since disappearance rates differed according to body mass, and the effect of the time elapsed since carcass placement changed between body-size classes. Only *c.* 2% of very small birds (< 100g), such as chicks of Domestic Chicken, remained 30 days after they were placed in the field. Persistence rates increased

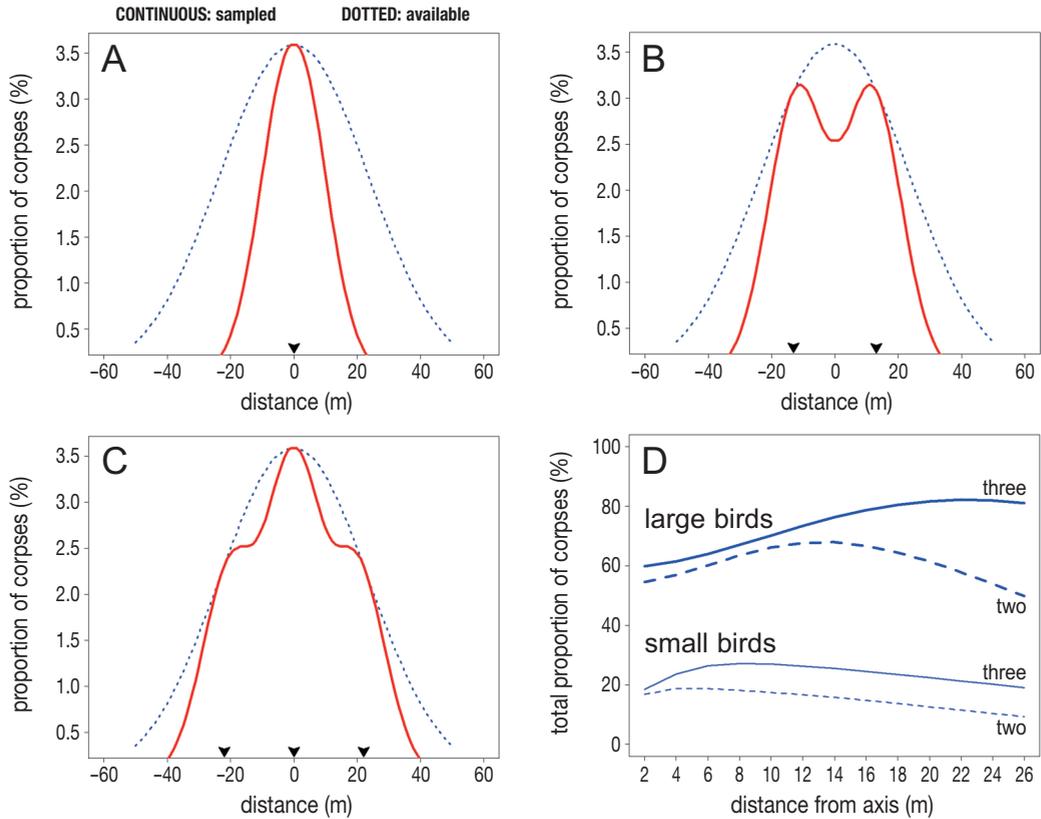


FIG. 5.—Proportion of carcasses detected around high-voltage electric lines belonging to large/very large birds (*i.e.* larger than an Eurasian Stone-curlew *Burhinus oedicnemus*, > 35cm), considering the dispersion patterns depicted in Figure 2, and the detection probability presented in Figure 3 and Table 2. Y axis values for panels A, B and C refer to percentages at 1m distance intervals in the X axis. Positions of observers searching for carcasses are indicated by arrow points on the X axes. A: one observer walking below the line axis; B: two observers walking in parallel 13m either side of the line axis; C: three observers, one below the line axis of the electric line, other two walking in parallel 22m to either side of the electric line. D: total proportions of carcasses of small (mainly passerine < 100g and < 20cm in length; thin lines) and large/very large birds (thick lines) detected at different distances of separation from the line axis by two (dashed lines) or three (continuous lines) observers walking in parallel.

[Proporción de cadáveres detectados en los alrededores de las líneas de alta tensión pertenecientes a aves grandes/muy grandes (*i.e.* más grandes que el alcaraván común, > 35 cm), teniendo en cuenta los patrones de dispersión representados en la Figura 2, y la probabilidad de detección presentada en la Figura 3 y en la Tabla 2. Los valores en el eje Y para los paneles (A), (B) y (C) se refieren a los porcentajes de aves detectadas en intervalos de 1 m en el eje X. La posición de los observadores que buscan los cadáveres se muestra con flechas en los ejes de las X. A: un observador andando bajo el eje de la línea eléctrica. B: dos observadores andando en paralelo a 13 m del eje de la línea eléctrica. C: tres observadores, uno bajo el eje de la línea eléctrica, y dos andando en paralelo 22 m a cada lado de la línea eléctrica. D: proporción total de cadáveres de aves pequeñas (principalmente paseriformes < 100 g y < 20 cm de longitud; líneas finas) y grandes/muy grandes (líneas gruesas) detectados a distintas distancias de separación del eje de la línea eléctrica con dos (línea discontinua) y tres (línea continua) observadores andando en paralelo.]

to c. 50% for medium-sized birds such as Rock Pigeons or Common Quails, and to c. 80% for large birds such as Domestic Chickens (see Figure 4). Disappearance rates were higher in Fuerteventura than in Lanzarote, which is explained by the larger populations of avian scavengers, the Common Raven (Nogales & Nieves, 2007) and Egyptian Vulture (Palacios & Barone, 2007), on the former island. The absence of a clear and generalised seasonal effect on disappearance rates when comparing the dry and hot summer season (*i.e.* July, 2015) with the cooler and wetter early spring (*i.e.* March 2016) suggests that these rates can be generalised throughout the year.

## CONCLUSIONS

Accurate estimates of avian collision rates with electric lines should incorporate correction factors based on the three main bias sources affecting carcass counts: carcass dispersion around the electric line axis, carcass detectability and carcass removal by scavengers. In addition, species- and powerline-specific factors must be taken into account in order to apply these correction factors properly. Firstly, the search zone should be defined according to the height and the typology of the electric line, since dispersion distances of carcasses increase with cable height (*i.e.* dispersion is further at high-voltage lines and smaller birds disperse further away), thus enhancing cost-effectiveness while surveying electric lines in search of bird fatalities. Secondly, detection probability models should be considered as a complementary approach to estimating an effective strip width and the area actually covered while sampling for carcasses, in order to estimate the number of carcasses that go undetected. Lastly, carcass disappearance trials allow the estimation of disappearance rates after collision due to scavenger removal:

*c.* 2% of small birds, 50% of medium-sized birds and 80% of large birds remained in place 30 days after the fatality. Correction factors based on these and similar results should be taken into account in order not to severely underestimate the actual mortality rates of birds arising from collision with electric lines.

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**AUTHOR CONTRIBUTIONS.**—LMC, FG and VM designed the study. All authors conducted data collection and prepared the data. LMC and JG-C performed data analyses and wrote the paper. All authors reviewed and approved the final draft.

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#### Appendix 1.

**A.** Description of the zig-zag pattern during the search surveys under electric lines.

**B.** Description and photographs of the decomposition states of carcasses.

**Appendix 2.** Tables C1 and C2: Body masses and number of carcasses of species found during the search for carcasses under electric lines.

**Appendix 3.** R script.

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## SUPPLEMENTARY ELECTRONIC MATERIAL

ARDEOLA 68(1)

### FACTORS AFFECTING DIFFERENTIAL UNDERESTIMATES OF BIRD COLLISION FATALITIES AT ELECTRIC LINES: A CASE STUDY IN THE CANARY ISLANDS

### FACTORES QUE AFECTAN A LA SUBESTIMACIÓN DIFERENCIAL DE LAS COLISIONES DE AVES CON LÍNEAS ELÉCTRICAS: UN CASO DE ESTUDIO EN LAS ISLAS CANARIAS

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## APPENDIX 1. A

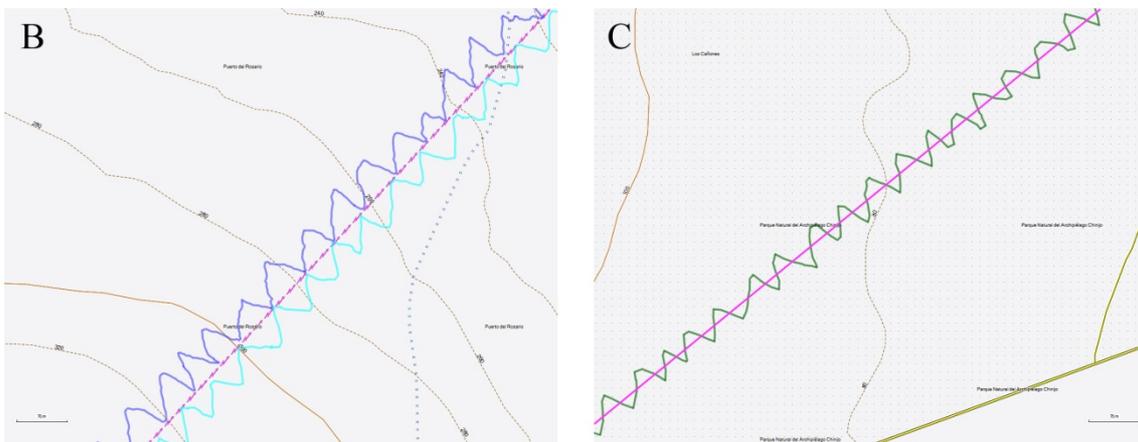
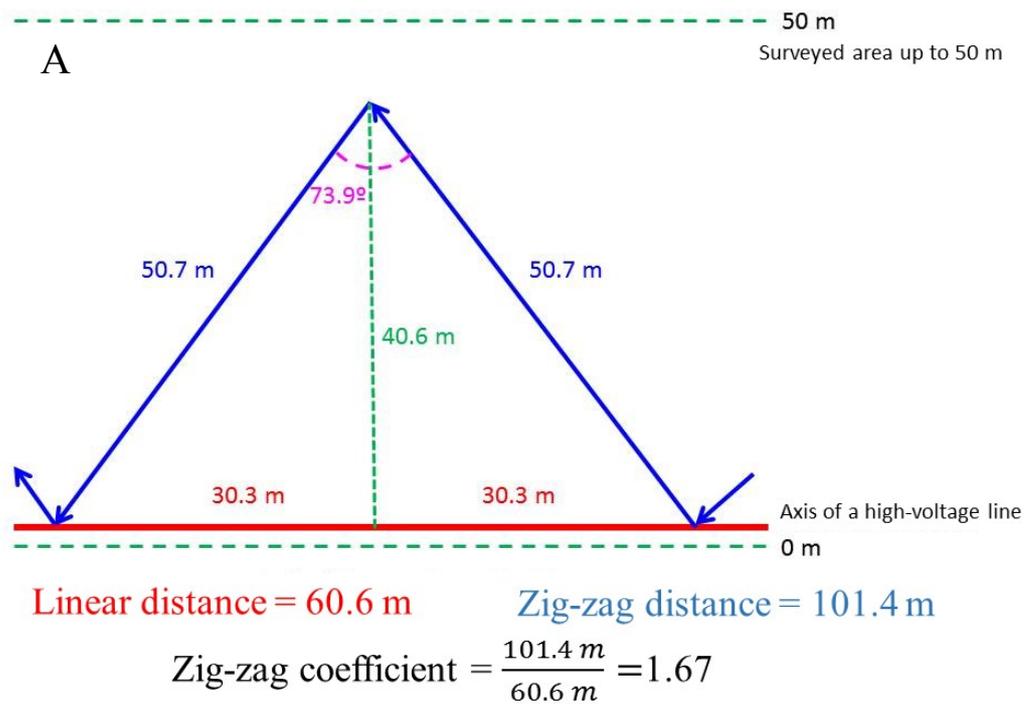
### Description of the zig-zag pattern during the search surveys under electric lines

***[Descripción del patrón de zigzageo seguido durante la prospección de las líneas eléctricas.]***

The mean zigzagging coefficient was 1.678, a ratio between the length of the zig-zag transect and the length of the power line (sd = 0.430; weighted mean of 152 randomly selected sections obtained in the three study periods), very close to that of x1.6 suggested by Red Eléctrica de España in the *Metodología y protocolos para la recogida y análisis de datos de siniestralidad de aves por colisión en líneas de transporte de electricidad*. Figure A1-A illustrates an "average" case of how the power lines were prospected. The average walking speed (including the time in movement and the time dedicated to recording the data of the carcasses and the characteristics of the power lines and their surroundings) was 2.46km/h (s.d. = 0.987; range: 1, 1-3.3 km/h). The percentage of time in movement was tremendously variable, mainly due to whether or not carcasses were found: 72% (s.d. = 31.1%; range: 40-92%). The average speed during movement was 3.39km/h (s.d. = 0.429). The average maximum separation of the researchers to the axis of the power line, the "knee" of the zigzag, was 40.6m (s.d. = 9.2m; estimate made on 400 randomly chosen points from six different observers). Although researchers, on average, walked up to 40.6m from the axis of the power line, they could look for carcasses further from that point in the "knee" of the zigzag, as shown in Figure A1-A.

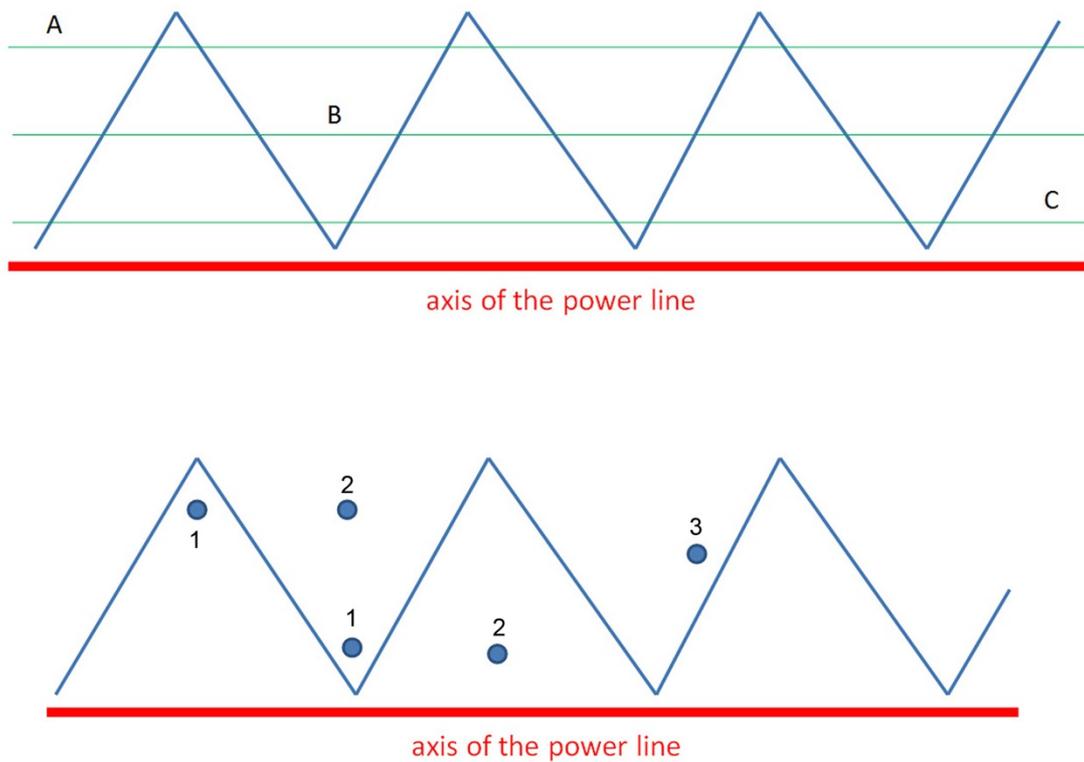
Zigzag survey is a sampling protocol that uniformly covers the study area. It is easily demonstrated by considering how any parallel line to the power line axis crosses the zigzag trail the same number of times irrespective of the perpendicular distance to the axis (see lines A, B and C in the upper part of Figure A2). Detection probability of a carcass is a matter of the distance to the observer, irrespective of the distance to the power line axis. Thus locations 1 in the lower part of Figure A2 (being very close or far away from the power line axis) are covered "more intensively" than 3, considering the curves of probability of detection in Figure 3 in the main document. Nevertheless, locations 2, at the same level as 1 with respect to the axis are "less intensively" covered than both 1 and 3. Averaging over a very large sample of transects and carcass locations,

the average distance of any location 1, 2, 3... to the zigzag is the same. Thus, some locations are over-covered near the legs, or knees, of the zigzag (locations 1), but there are also other locations (2) that are under-covered. By means of Monte Carlo simulations it is demonstrated that the average distance of any location to the zigzag line is the same irrespective of the distance to the power line axis, although the variance is higher near the knees of the zigzags. On the other hand, the average angle of the knee in the zigzags ( $74^\circ$ ) was broad enough to minimise the apparent problem of higher detections in locations near the "knees" of the zigzag.



**Figure A1.** Scheme of the zig-zag pattern followed during the prospection of electric lines. (A) Mean characteristics of the zig-zag transects. The linear distance (red), zig-zag distance (blue), angle (pink) and the maximum distance from the axis of the electric line (green), are shown. (B) Scheme of the tracks (blue) followed by two observers prospecting a high-voltage line in parallel. (C) Scheme of the track (green) followed by one observer prospecting a medium-voltage or telephone line.

**Figura A1.** Esquema del patrón de zigzageo seguido durante la prospección de las líneas eléctricas. (A) Características medias de los transectos en zig-zag. Se representa la distancia lineal (rojo), la distancia en zig-zag (azul), el ángulo (rosa) y la distancia máxima desde el eje de la línea eléctrica (verde). (B) Esquema de los transectos (azul) seguidos por dos observadores que prospectaron en paralelo una línea de alta tensión. (C) Esquema de un transecto (verde) seguido por un observador prospectando una línea de media tensión o telefónica.



**Figure A2.** Scheme of the zig-zag pattern followed during the prospection of electric lines. At the top, the figure illustrates the uniform survey of the sampling area under the zig-zag pattern. At the bottom, the graph shows the potential location of carcasses with respect of the axis and the zig-zag transect (*i.e.* the observer), exposing contrasting scenarios where locations are over-sampled or under-sampled.

**Figura A2.** Esquema del patrón de zig-zageo seguido durante la prospección de las líneas eléctricas. En la parte superior, la figura representa el muestreo uniforme del área muestreada bajo un patrón de zig-zageo. En la parte inferior, el gráfico representa la localización potencial de los cadáveres con respecto al eje y al transecto en zig-zag (*i.e.* el observador), representando diferentes escenarios donde las localizaciones son sobre muestreadas o infra muestreadas.

## APPENDIX 1. B.

**Description and photographs of the decomposition states of carcasses.**  
*[Descripción y fotografías de los estados de descomposición de los cadáveres.]*

State 1 or fresh is characterised by the presence of soft tissues, covering from time of death to body inflammation due to bacterial fermentation (Fig. B1).



**Figure B1.** Carcass of Rock Pigeon *Columba livia* in decomposition state 1 or fresh.

*[Cadáver de una paloma bravía Columba livia en estado de descomposición 1 o fresco.]*

State 2 or *emphysematous* included from the beginning of inflammation caused by bacterial fermentation until body rupture due to pressure and superficial tissue decomposition (Fig. B2).



**Figure B2.** Carcass of Domestic Chicken *Gallus gallus domesticus* in decomposition state 2 or *emphysematous*.

[Cadáver de una gallina doméstica *Gallus gallus domesticus* en estado de descomposición 2 o *enfisematoso*.]

State 3 or *coliculative* encompassing from gas release until decomposition and disappearance of soft tissues (Fig. B3).



**Figure B3.** Carcass of Domestic Chicken *Gallus gallus domesticus* in decomposition state 3 or *coliculative*

[Cadáver de una gallina doméstica *Gallus gallus domesticus* en estado de descomposición 3 o *colicutivo*.]

State 4 or *post-colicuative* only dried tissues, cartilages and bones remain (Fig. B4).



**Figure B4.** Carcass of Domestic Chicken *Gallus gallus domesticus* in decomposition state 4 or *post-colicuative*.

[Cadáver de una gallina doméstica *Gallus gallus domesticus* en estado de descomposición 4 o *post-colicuativo*.]

State 5 or *skeletal reduction* occurred when only bone remains are distinguishable (Fig. B5).



**Figure B5.** Carcass of Domestic Chicken *Gallus gallus domesticus* in decomposition state 5 or *skeletal reduction*

[Cadáver de una gallina doméstica *Gallus gallus domesticus* en estado de descomposición 5 o reducción esquelética.]

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## APPENDIX 2.

**Tables C1 and C2: Body masses and number of carcasses of species found during the search for carcasses under electric lines**

***Tablas C1 y C2: Masas corporales y número de cadáveres de las especies encontradas durante la búsqueda de cadáveres bajo las líneas eléctricas.***

**Table C1.** Body mass per species found during electric lines prospection. Body masses are shown in grams and were obtained from Perrins (1998).

**Tabla C1.** Masa corporal para cada una de las especies encontradas durante la prospección de las líneas eléctricas. Se muestran las masas corporales en gramos obtenidas de Perrins (1998).

<b>Species</b>	<b>Body mass (g)</b>
Barbary Partridge <i>Alectoris barbara</i>	480.0
Berthelot's Pipit <i>Anthus berthelotii</i>	16.5
Black-bellied Sandgrouse <i>Pterocles orientalis</i>	474.0
Bulwer's Petrel <i>Bulweria bulwerii</i>	93.0
Cattle Egret <i>Bubulcus ibis</i>	340.0
Common Buzzard <i>Buteo buteo</i>	806.5
Common Hoopoe <i>Upupa epops</i>	59.8

Common Kestrel <i>Falco tinnunculus</i>	174.5
Common Raven <i>Corvus corax</i>	1250.0
Cream-coloured Courser <i>Cursorius cursor</i>	108.0
Egyptian Vulture <i>Neophron percnopterus</i>	2035.0
Eurasian Collared-dove <i>Streptopelia decaocto</i>	196.0
Eurasian Stone-curlew <i>Burhinus oedicnemus</i>	461.0
European Turtle Dove <i>Streptopelia turtur</i>	125.0
Grey Heron <i>Ardea cinerea</i>	1433.0
Houbara Bustard <i>Chlamydotis undulata</i>	1245.0
Iberian Grey Shrike <i>Lanius meridionalis</i>	63.5
Lesser Short-toed Lark <i>Calandrella rufescens</i>	23.3
Northern Gannet <i>Morus bassanus</i>	2950.0
Rock Dove <i>Columba livia</i>	216.0
Cory's Shearwater <i>Calonectris borealis</i>	645.0
Unknown Species (Very large-sized)	900.0
Unknown Species (Medium-sized)	300.0
Yellow-legged Gull <i>Larus michahellis</i>	895.0

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**Table C2.** Number of carcasses found per species during electric lines prospection. The number of carcasses is shown independently for each island (Fuerteventura and Lanzarote) and each sampling period (i.e. March 2015, December/November 2015 and March 2016).

**Tabla C2.** Número de cadáveres por especie encontrados durante la prospección de las líneas eléctricas. Se muestra el número de cadáveres independientemente para cada isla (Fuerteventura y Lanzarote) y para cada periodo de muestreo (i.e. marzo 2015, diciembre/noviembre 2015 y marzo 2016).

	FUERTEVENTURA				LANZAROTE				Total
	Jul-15	Nov/Dec-15	Mar-16	Total	Jul-15	Nov/Dec-15	Mar-16	Total	
Barbary Partridge <i>Alectoris barbara</i>	1	0	5	<b>6</b>	0	2	3	5	<b>11</b>
Berthelot's Pipit <i>Anthus berthelotii</i>	1	1	1	<b>3</b>	2	0	0	2	<b>5</b>
Black-bellied Sandgrouse <i>Pterocles orientalis</i>	0	0	9	<b>9</b>	0	0	0	0	<b>9</b>
Bulwer's Petrel <i>Bulweria bulwerii</i>	2	0	0	<b>2</b>	7	0	0	7	<b>9</b>
Cattle Egret <i>Bubulcus ibis</i>	2	0	1	<b>3</b>	3	15	18	36	<b>39</b>
Common Buzzard <i>Buteo buteo</i>	0	2	0	<b>2</b>	0	0	0	0	<b>2</b>
Common Hoopoe <i>Upupa epops</i>	0	0	5	<b>5</b>	0	0	0	0	<b>5</b>
Common Kestrel <i>Falco tinnunculus</i>	0	0	0	<b>0</b>	2	1	0	3	<b>3</b>
Common Raven <i>Corvus corax</i>	4	5	3	<b>12</b>	0	2	1	3	<b>15</b>
Cream-coloured Courser <i>Cursorius cursor</i>	2	0	0	<b>2</b>	0	0	0	0	<b>2</b>
Egyptian Vulture <i>Neophron percnopterus</i>	0	1	3	<b>4</b>	0	0	0	0	<b>4</b>
Eurasian Collared-dove <i>Streptopelia decaocto</i>	2	4	3	<b>9</b>	0	1	1	2	<b>11</b>
Eurasian Stone-curlew <i>Burhinus oedicanus</i>	7	2	11	<b>20</b>	5	7	4	16	<b>36</b>
European Turtle Dove <i>Streptopelia turtur</i>	1	0	2	<b>3</b>	0	0	0	0	<b>3</b>
Grey Heron <i>Ardea cinerea</i>	0	0	0	<b>0</b>	0	1	1	2	<b>2</b>
Houbara Bustard <i>Chlamydotis undulata</i>	4	2	6	<b>12</b>	11	8	6	25	<b>37</b>
Iberian Grey Shrike <i>Lanius meridionalis</i>	2	0	1	<b>3</b>	1	0	1	2	<b>5</b>
Lesser Short-toed Lark <i>Calandrella rufescens</i>	0	1	0	<b>1</b>	0	0	0	0	<b>1</b>

	FUERTEVENTURA				LANZAROTE				Total
	Jul-15	Nov/Dec-15	Mar-16	Total	Jul-15	Nov/Dec-15	Mar-16	Total	
Northern Gannet <i>Morus bassanus</i>	1	0	0	<b>1</b>	0	0	0	0	<b>1</b>
Rock Dove <i>Columba livia</i>	15	26	47	<b>88</b>	10	18	17	45	<b>133</b>
Cory's Shearwater <i>Calonectris borealis</i>	0	5	7	<b>12</b>	2	1	3	6	<b>18</b>
Unknown Species (Very large-sized)	2	0	0	<b>2</b>	0	0	1	1	<b>3</b>
Unknown Species (Medium-sized)	0	6	7	<b>13</b>	0	4	3	7	<b>20</b>
Yellow-legged Gull <i>Larus michahellis</i>	16	16	13	<b>45</b>	2	2	8	12	<b>57</b>
<b>Total</b>	<b>62</b>	<b>71</b>	<b>124</b>	<b>257</b>	<b>45</b>	<b>62</b>	<b>67</b>	<b>174</b>	<b>431</b>

## SUPPLEMENTARY ELECTRONIC MATERIAL

ARDEOLA 68(1)

### FACTORS AFFECTING DIFFERENTIAL UNDERESTIMATES OF BIRD COLLISION FATALITIES AT ELECTRIC LINES: A CASE STUDY IN THE CANARY ISLANDS

FACTORES QUE AFECTAN A LA SUBESTIMACIÓN DIFERENCIAL DE LAS COLISIONES DE AVES CON LÍNEAS ELÉCTRICAS: UN CASO DE ESTUDIO EN LAS ISLAS CANARIAS

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## APPENDIX 3.

### R script (Código de R)

R script for the estimation of the proportion of large/very large carcasses (*i.e.* larger than an Eurasian Stone Curlew *Burhinus oedicanus* > 35cm) detected around high-voltage power lines, considering the dispersion patterns depicted in Figure 2 in the main document, and the detection probability presented in Figure 3 and Table 2.

```
library(fdrtool)

## "Those who can, do; those who can't - use computer simulation". George
## Bernard Shaw

set.seed(111)

## dispersion distances of corpses (Figure 2)
mean_distances <- 18.316
sd_distances <- 14.425
sd_distances / mean_distances    ## half-normal if the ratio is ca.
sqrt((pi-2)/2) = 0.7555
##
corpses_3 <- rhalfnorm(n=10000000, theta=1/mean_distances)
max(corpses_3)
hist(corpses_3)
corpses_2 <- subset(corpses_3, corpses_3<=50)
corpses <- c(-corpses_3, corpses_3)
##
b <- c(-50:50)
bins.corpses <- .bincode(corpses, b, TRUE)
table.corpses <- as.data.frame(aggregate(corpses ~ as.factor(bins.corpses),
FUN=length))
names(table.corpses)[1] <- "distance_m"
maximum <- max(table.corpses$corpses)
summatory <- sum(table.corpses$corpses)
table.corpses$probability <- table.corpses$corpses/maximum
table.corpses$percentage_2 <- table.corpses$corpses/summatory*100
table.corpses$percentage <- table.corpses$corpses/(summatory/2)*100
table.corpses$distance_m <- c(-50:-1, 1:50)
table.corpses

## detection distances of large carcasses (panels C and D in Figure 3)
mean_detections <- 8.295455
sd_detections <- 6.211149
sd_detections / mean_detections    ## half-normal if the ratio is ca.
sqrt((pi-2)/2) = 0.7555
##
carcasses_3 <- rhalfnorm(n=10000000, theta=1/mean_detections)
max(carcasses_3)
hist(carcasses_3)
carcasses_2 <- subset(carcasses_3, carcasses_3<=30)
carcasses <- c(-carcasses_3, carcasses_3)
##
b <- c(-50:50)
bins.carcasses <- .bincode(carcasses, b, TRUE)
```

```

table.carcasses <- as.data.frame(aggregate(carcasses ~
as.factor(bins.carcasses), FUN=length))
names(table.carcasses)[1] <- "distance_m"
maximum.c <- max(table.carcasses$carcasses)
table.carcasses$probability <- table.carcasses$carcasses/maximum.c
table.carcasses$distance_m <- c(-50:-1, 1:50)
table.carcasses

## with only ONE researcher below the power line axis
prop_corpses_detected <- table.carcasses$probability *
table.corpses$percentage
##
plot(table.corpses$distance_m, table.corpses$probability)
plot(table.carcasses$distance_m, table.carcasses$probability)
plot(table.corpses$distance_m, prop_corpses_detected)
##
sum(table.corpses$percentage)/2
sum(prop_corpses_detected)/2
plot(table.corpses$distance_m, table.corpses$percentage, col="blue",
xlim=c(-60, 60), cex=0, cex.main=2, cex.axis=1.5, main="CONTINUOUS: sampled
DOTTED: available")
lines(table.corpses$distance_m, table.corpses$percentage, col="blue",
lwd=4, lty=3)
lines(table.corpses$distance_m, prop_corpses_detected, col="red", lwd=6)

## with TWO researchers, both at D distance from the axis of the power line
D <- 15 ## put here the distance from the axis of the power line in
meters
##
## left and right researchers
table.carcasses.left <- table.carcasses
table.carcasses.left$distance_m <- table.carcasses.left$distance_m - D
table.carcasses.left <- subset(table.carcasses.left,
table.carcasses.left$distance_m >= -50)
table.carcasses.left.zeros <- data.frame(c((50-D+1):50), rep(0, times=D),
rep(0, times=D))
names(table.carcasses.left.zeros) <- names(table.carcasses.left)
table.carcasses.left <- rbind(table.carcasses.left,
table.carcasses.left.zeros)
##
table.carcasses.right <- table.carcasses
table.carcasses.right$distance_m <- table.carcasses.right$distance_m + D
table.carcasses.right <- subset(table.carcasses.right,
table.carcasses.right$distance_m <= 50)
table.carcasses.right.zeros <- data.frame(c(-50:(-50+D-1)), rep(0,
times=D), rep(0, times=D))
names(table.carcasses.right.zeros) <- names(table.carcasses.right)
table.carcasses.right <- rbind(table.carcasses.right.zeros,
table.carcasses.right)
## compound of probabilities
prob_corpses_detected.2 <- table.carcasses.left$probability + (1-
table.carcasses.left$probability)*table.carcasses.right$probability
prop_corpses_detected.2 <- prob_corpses_detected.2 *
table.corpses$percentage
##
sum(table.corpses$percentage)/2
sum(prop_corpses_detected.2)/2

```

```

plot(table.corpses$distance_m, table.corpses$percentage, col="blue",
xlim=c(-60, 60), cex=0, cex.main=2, cex.axis=1.5, main="CONTINUOUS: sampled
DOTTED: available")
lines(table.corpses$distance_m, table.corpses$percentage, col="blue",
lwd=4, lty=3)
lines(table.corpses$distance_m, prop_corpses_detected.2, col="red", lwd=6)

```

```

## with THREE researchers, one below the power line axis, and two at D
distance from the axis of the power line
D <- 25 ## put here the distance from the axis of the power line in
meters
##
## central researcher
table.carcasses$probability
##
## left and right researchers
table.carcasses.left <- table.carcasses
table.carcasses.left$distance_m <- table.carcasses.left$distance_m - D
table.carcasses.left <- subset(table.carcasses.left,
table.carcasses.left$distance_m >= -50)
table.carcasses.left.zeros <- data.frame(c((50-D+1):50), rep(0, times=D),
rep(0, times=D))
names(table.carcasses.left.zeros) <- names(table.carcasses.left)
table.carcasses.left <- rbind(table.carcasses.left,
table.carcasses.left.zeros)
##
table.carcasses.right <- table.carcasses
table.carcasses.right$distance_m <- table.carcasses.right$distance_m + D
table.carcasses.right <- subset(table.carcasses.right,
table.carcasses.right$distance_m <= 50)
table.carcasses.right.zeros <- data.frame(c(-50:(-50+D-1)), rep(0,
times=D), rep(0, times=D))
names(table.carcasses.right.zeros) <- names(table.carcasses.right)
table.carcasses.right <- rbind(table.carcasses.right.zeros,
table.carcasses.right)
##
## compound of probabilities
prob_corpses_detected.2 <- table.carcasses.left$probability + (1-
table.carcasses.left$probability)*table.carcasses.right$probability
prob_corpses_detected.3 <- table.carcasses$probability + (1-
table.carcasses$probability)*prob_corpses_detected.2
prop_corpses_detected.3 <- prob_corpses_detected.3 *
table.corpses$percentage
##
sum(table.corpses$percentage)/2
sum(prop_corpses_detected.3)/2
plot(table.corpses$distance_m, table.corpses$percentage, col="blue",
xlim=c(-60, 60), cex=0, cex.main=2, cex.axis=1.5, main="CONTINUOUS: sampled
DOTTED: available")
lines(table.corpses$distance_m, table.corpses$percentage, col="blue",
lwd=4, lty=3)
lines(table.corpses$distance_m, prop_corpses_detected.3, col="red", lwd=6)

```