The effects of powerlines on bustards: how best to mitigate, how best to monitor?†

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Summary

Bustards comprise a highly threatened family of birds and, being relatively fast, heavy fliers with very limited frontal visual fields, are particularly susceptible to mortality at powerlines. These infrastructures can also displace them from immediately adjacent habitat and act as barriers, fragmenting their ranges. With geographically ever wider energy transmission and distribution grids, the powerline threat to bustards is constantly growing. Reviewing the published and unpublished literature up to January 2021, we found 2,774 records of bustard collision with powerlines, involving 14 species. Some studies associate powerline collisions with population declines. To avoid mortalities, the most effective solution is to bury the lines; otherwise they should be either routed away from bustard-frequented areas, or made redundant by local energy producers. When possible, new lines should run parallel to existing structures and wires should preferably be as low and thick as possible, with minimal conductor obstruction of vertical airspace, although it should be noted that these measures require additional testing. A review of studies finds limited evidence that ‘bird flight diverters’ (BFDs; devices fitted to wires to induce evasive action) achieve significant reductions in mortality for some bustard species. Nevertheless, dynamic BFDs are preferable to static ones as they are thought to perform more effectively. Rigorous evaluation of powerline mortalities, and effectiveness of mitigation measures, need systematic carcass surveys and bias corrections. Whenever feasible, assessments of displacement and barrier effects should be undertaken. Following best practice guidelines proposed with this review paper to monitor impacts and mitigation could help build a reliable body of evidence on best ways to prevent bustard mortality at powerlines. Research should focus on validating mitigation measures and quantifying, particularly for threatened bustards, the population effects of powerline grids at the national scale, to account for cumulative impacts on bustards and establish an equitable basis for compensation measures.

Introduction

Bustards are amongst the most endangered groups of birds in the world, threatened by hunting, habitat degradation and loss, disturbance, and infrastructure development such as roads, windfarms, solar farms, and especially overhead powerlines (Collar et al. 2017). Overhead powerlines pose a significant collision risk for bustards, and are identified as a major source of non-natural mortality (Jenkins et al. 2010, Martin and Shaw 2010, Bernardino et al. 2018, Marcelino et al. 2018). With the expansion of electricity grids globally, driven by political, economic, egalitarian, and humanitarian considerations, and notably with the development of renewable power sources to reduce carbon emissions, there is a rapidly rising concern over the severity of the impacts of utility infrastructures on birds, and over the ways these impacts can be mitigated (Bernardino et al. 2018), particularly for species such as bustards that are exceptionally susceptible to powerline collisions.

Multiple variables affect this kind of susceptibility in birds (review in Bernardino et al. 2018). Environmental factors, both spatial and temporal, including topography and habitat features

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(APLIC 2012) and light levels, weather conditions, season, and
phenology (e.g. Shaw et al. 2013), all play a role. The behaviour
of the birds themselves is also important, as nocturnal flights may
result in higher collision rates (Murphy et al. 2016a). The position
(in a vertical or horizontal configuration), height and conspicuous-
ness of wires all contribute an effect (e.g. Bevanger 1994, Marques
et al. 2021). Birds that fly in flocks appear to be at higher risk,
possibly because the tendency to follow leaders overrides individual
vigilance (e.g. Drewitt and Langston 2008). Species with larger
biometrics such as weight and wing-load are associated with faster
flight and lower manoeuvrability, and are therefore at greater risk
(e.g. Bevanger 1998). Those in which frontal visual fields are
reduced are also at greater risk (Martin and Shaw 2010). Bustards
combine these various behavioural and morphological disadvan-
tages, being gregarious during much of their annual cycle, and
relatively heavy mid-sized to large birds with very limited binocular
frontal visual fields (Martin and Shaw 2010).

The commonest measure to mitigate bird mortality by collisions
with powerlines is the marking of the conductor wires and earth
wire with devices commonly called 'bird flight diverters' (BFDs),
which aim to provide a sufficiently strong visual signal to induce
evasive action in an approaching bird (Barrientos et al. 2011,
Bernardino et al. 2018). However, the efficacy of this mitigation
varies greatly with device design, environment, and target species
(Jenkins 2010, Bernardino et al. 2019); it is widely apparent that
BFDs may ease but do not solve the problem for certain species.
Moreover, powerlines may also cause displacement effects involv-
ing reductions in bird abundance or in the degree of occupancy
of suitable habitat adjacent to the infrastructure (Silva et al. 2010,
Lóránt and Vadász 2014). One hypothesis explaining this pattern
relates to the use or preference of pylons and poles by raptors for
perching, providing advantageous views for scanning the sur-
rounding landscape, which may render it unattractive or unusable
for prey species (Silva et al. 2010). In some situations, these tall
structures (whose size varies mostly with voltage level and wire
configuration) also act as barriers, changing regular flight move-
ments between bisected patches of habitat (Pruet et al. 2009, Raab
et al. 2011).

The impact of powerlines on bustard populations seriously
compounds other major threats such as habitat change, hunting
and poaching, and predation, particularly for those species that are
at highest risk (Collar et al. 2017). However, despite the issue long
being flagged as a conservation challenge (APLIC 2012) and the
accumulation of a considerable body of literature on the subject
(review in Bernardino et al. 2018), information on how powerlines
and mitigation measures affect bustards in particular remains scant.
Consequently, with the present rapid expansion of electricity grids,
planners and conservationists are being forced to take decisions on
the deployment and management of powerlines in bustard-
occupied landscapes without access to scientifically validated spe-
cifications. Experience is restricted to western Europe, southern
Africa, and some parts of Asia, while guidance on monitoring and
mitigating powerline impacts on bustards has until now been
unavailable to conservation practitioners.

This paper encompasses two distinct sections. In the first we
review all available evidence on the impacts of powerlines on
bustards, including mortality, displacement, and population effects
based on both peer-reviewed and grey literature. In the second we
outline best practice and, based on our cumulative experience,
make recommendations for assessing the impacts of powerlines
on bustards and for implementing and monitoring mitigation
measures. We further suggest approaches for future research in
this emerging area of conservation concern.

Review of the impacts of powerlines on bustards

Methods

To compile data on the effects of powerlines on bustard species we
followed two complementary approaches. First, we undertook a
systematic literature review, through the compilation of peer-
reviewed studies from the search engines ISI Web of Knowledge
and Scopus. The search was carried out in January 2021, with the
term ‘line’ or ‘wire’ combined with one of the following key words:
referring to interactions between bustards and powerlines were
considered in our analysis. Second, as this review was restricted
to literature in English, we consulted with professionals working on
the effects of powerlines on bustards (and on birds in general). We
particularly targeted regions under-represented in peer-reviewed
studies, such as eastern Europe, Asia, and Africa (except
South Africa), and sought to collect data that were dispersed in
non-ISI documents and those unavailable in English. The steps
followed to identify, screen, and include studies are represented in
a PRISMA flow diagram (Paige et al. 2020) in Figure S1 in the online
supplementary material. Whenever possible, the resulting informa-
tion was assigned to two powerline types: (i) ‘transmission lines’,
which carry electricity at high voltages (>60 kV) from generating
facilities to substations, and (ii) ‘distribution lines’, which deliver
electricity from substations to consumer hubs at lower voltages
(<60 kV) (IEA 2016). Typically, transmission lines are taller and
wider, have a larger number of conductor wires and include thinner,
less visible earth wires (i.e. wires that provide an electrical
connection to the ground, hence also called ground wires, but
which are usually positioned above conductor wires).

Results

We found a total of 79 studies, most of them in the grey literature
(55%) reporting effects of overhead wires in bustards. The earliest
record dates back to 1884 and refers to collisions of Little Bustards
Tetrax tetrax with telephone wires, but this topic becomes more
frequent after the year 2000 (94% after 2000, 63% after 2010).

Mortality by collision

All evidence on mortalities resulting from bustard collisions with
powerlines, from both systematic monitoring studies and inciden-
tal records, was assembled, supplementing Mahood et al. (2018)
and Silva et al. (2022). Most sources merely reported mortality
events and did not estimate collision rates for species, account for
survey bias, or clearly report survey effort. Comparisons among
studies or species are therefore limited and subject to bias.

We collected 2,774 records of collisions with powerlines (almost
always mortality events) involving 14 of the 26 bustard species
(taxonomy following del Hoyo and Collar 2014), spanning IUCN
Red List categories from ‘Least Concern’ to ‘Critically Endangered’
(Table 1, with details in Table S1). Most records involve European
and southern African species or populations. We found no evidence
from central Africa or Australia (although we found a collision with
a telephone wire by the Australian Bustard Ardeotis australis, a 15th
Table 1. Summary of collision events with powerlines by bustard species (total mortality events: 2,769 individuals). Species, species range and 2021 IUCN Red List category are given based on BirdLife International (2021); Great Bustard broken into two subspecies but Red List category applies to the species. Line type: TX – transmission powerlines, DX – distribution powerlines. Number of collisions observed: total number of collision events compiled for each species. Percentage tracked individuals: powerline victims with GPS telemetry devices per study or by several studies (mean and range presented). Sources: studies or experts providing data on bustard collisions.

<table>
<thead>
<tr>
<th>Species</th>
<th>2021 IUCN status</th>
<th>Geographic range</th>
<th>Region/country with collision data</th>
<th>Line type</th>
<th>Number of collisions observed</th>
<th>Percentage tracked individuals</th>
<th>Sources</th>
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<tr>
<td>Tetrax tetrax</td>
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<td>Otis tarda dybowskii</td>
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<td>Otis tarda tarda</td>
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<td>Chlamydotis undulata</td>
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<td>Asian Houbara</td>
<td>VU</td>
<td>Middle East–Eurasia</td>
<td>Central Asia, Iran, Uzbekistan</td>
<td>TX; DX</td>
<td>21</td>
<td>4.41% (1.92–6.9)</td>
<td>Burnside et al. (2015, 2018), Kolnegari et al. (2020)</td>
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<td>Chlamydotis macqueenii</td>
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<th>Species</th>
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<th>Region/country with collision data</th>
<th>Line type</th>
<th>Number of collisions observed</th>
<th>Percentage tracked individuals</th>
<th>Mean (range)</th>
<th>Sources</th>
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<tr>
<td>Denham’s Bustard Neotis denhami</td>
<td>NT</td>
<td>Sahel, Central &amp; southern Africa</td>
<td>South Africa</td>
<td>TX; DX</td>
<td>18</td>
<td>–</td>
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<td>Shaw et al. (2010)</td>
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<tr>
<td>Great Indian Bustard Ardeotis nigriceps</td>
<td>CR</td>
<td>Asia</td>
<td>India</td>
<td>TX</td>
<td>11</td>
<td>–</td>
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<td>Uddin et al. (2021), State Forest Department in Uddin et al. (2021), ERDS Foundation in Uddin et al. (2021), D. Gadchavi (TCF) pers. com., Habib in Uddin et al. (2021), Patil (2014)</td>
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<td>Bengal Florican Houbaropsis bengalensis</td>
<td>CR</td>
<td>Asia</td>
<td>Cambodia</td>
<td>TX</td>
<td>6</td>
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<td>S. Mahood pers. comm.</td>
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<tr>
<td>Lesser Florican Sypheotides indicus</td>
<td>CR</td>
<td>Asia</td>
<td>India</td>
<td>n.a.</td>
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<td>BirdLife (2001), Kasambe and Gahale (2010), Ram et al. (2022)</td>
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<td>Southern Black Bustard Afrotis atra</td>
<td>VU</td>
<td>Southern Africa</td>
<td>South Africa</td>
<td>TX; DX</td>
<td>4</td>
<td>–</td>
<td></td>
<td>Shaw et al. (2010, 2018)</td>
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<tr>
<td>Blue Bustard Eupodotis caerulescens</td>
<td>NT</td>
<td>Southern Africa</td>
<td>South Africa</td>
<td>TX</td>
<td>9</td>
<td>–</td>
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<td>Shaw et al. (2021)</td>
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species; see Table S2), presumably reflecting the lower density of powerlines and/or lower number of relevant studies in these regions. The southern African Ludwig’s Bustard Neotis ludwigii produced the largest number of mortality records (c.56%), followed by the Palearctic members of the family, Little Bustard, Great Bustard Otis tarda, African Houbara Chlamydotis undulata and Asian Houbara C. macqueenii.

Collisions were reported for both transmission and distribution powerlines (Figure 1), but also for telephone, telegraph, and railway wires (n = 98, details in Table S2). Two studies conflated mortalities on powerlines, telephone wires and fences (Ashbrook et al. 2016, Gómez-Catasús et al. 2020). When identified in or identifiable from reports, transmission lines caused 1,963 collisions compared to 429 caused by distribution lines. These figures do not necessarily reflect the relative danger posed by the two types of line; rather they could simply reflect the greater attention given to the larger transmission lines. In fact, the highest record of collision events per km was reported for Little Bustards at a telephone wire in a single survey in Azerbaijan, where the largest known wintering flocks of this species concentrate (Ivanov and Priklonskii 1965). It should also be noted that the distribution grid is much larger (e.g. in Alentejo, Portugal, almost 10 times larger than that for transmission; Marques et al. 2021), potentially representing an overall higher mortality risk. Additionally, two or more transmission lines and distribution lines often run in parallel, making it difficult to establish the structure responsible for the collision.

Displacement and barrier effects

We found only six studies, all European, that specifically address powerline displacement effects on bustards, involving two species, namely Great Bustard (Lane et al. 2001, Magaña et al. 2010, Lóránt and Vadász 2014) and Little Bustard (Silva et al. 2010, Santos et al. 2016, Alonso et al. 2020). Displaying male Great Bustards avoid sites located within 400 m of medium-voltage powerlines, and occupy areas within 500–1,000 m of them less than expected (Lóránt and Vadász 2014), while the densities of displaying male Little Bustards decline with increasing proximity to transmission powerlines (Silva et al. 2010, Santos et al. 2016). As noted, such displacements may reflect the increased risk posed by raptors perching on the structures (Stahlecker 1978, Lammers and Collopy 2007), particularly during the breeding season, as minimising predation risk is crucial in nest-site selection (Magaña et al. 2010). However, Little Bustards do not seem to avoid powerlines when selecting stopover areas, possibly because some perform post-breeding dispersal movements at night, when they cannot detect these structures (Alonso et al. 2020).

Raab et al. (2011) found that take-off flight directions of Great Bustards are influenced by the presence of powerlines at c.800 m, and up to 1,600 m. This behaviour may reduce the risk of collision, but it also reveals how powerlines can become barriers, fragmenting habitat by conditioning the movements of local populations, potentially at wide spatial scales (Raab et al. 2011).

Population, behavioural and demographic effects

Mortality at powerlines is often cited as a probable factor in local bustard population declines (e.g. Pinto et al. 2005, Collar et al. 2017, WII 2018). However, the effects of powerlines on bustards are difficult to quantify through population approaches, specifically when aiming to assess the rate of decline caused by the infrastructure,
because they require demographic and biological data that are often unavailable. Several studies finding apparently unsustainable collision rates were unable to establish a causal link between collision rates and population declines (e.g. Jenkins et al. 2011, Marcelino et al. 2018, Shaw et al. 2018). However, a recent population viability analysis (PVA) in Rajasthan, India, estimated an annual mortality rate of 16% for the Great Indian Bustard Ardeotis nigriceps owing to powerlines, demonstrating that this would lead to the extinction of this species within 20 years (Uddin et al. 2021). Complementarily, a PVA found that the Great Bustard population near Madrid, Spain, would increase 1.7 times in 100 years in the absence of powerline collisions (Martín 2008).

The effect of collisions on overall annual survival has been evaluated in some species. At least 11–15% of South Africa’s Ludwig’s Bustards were estimated to be killed annually by transmission lines alone (Jenkins et al. 2011). GPS loggers on Iberian Little Bustards established that 3.4–3.8% of adult birds die annually at powerlines (Marcelino et al. 2018). In south-west Iberia densities of the species vary inversely with powerline density, possibly attributable to avoidance behaviour, increased mortality, or both (Marques et al. 2020).

Spatial and temporal clustering of bustard mortalities is often associated with specific times of the year when birds gather in larger numbers and undertake migration (e.g. Ivanov and Prikhonskii 1965, Shaw et al. 2018, Marques et al. 2021). Across Spain in the years 1997–2012 the effect was sufficiently great to increase the proportion of sedentary vs migratory Great Bustards, owing to the latter group’s higher mortality at powerlines (Palacín et al. 2017).

Many bustard species display sexual size dimorphism which may in theory result in differential collision rates between the sexes. Males, which are typically heavier, and therefore presumably less manoeuvrable in flight, are probably at greater risk than females. Collision rates in Western Great Bustards Otis tarda tarda and Ludwig’s Bustards are higher in males than females (Martin et al. 2007, Jenkins et al. 2011, Shaw et al. 2018), although this finding was not confirmed for the Kori Bustard Ardeotis kori (Shaw et al. 2018) or in a short Namibian study of Ludwig’s (J. Pallett unpubl. data). On the other hand, longer migrations are undertaken by the smaller sex in some bird species (e.g. Ketterson and Nolan 1976), and this is documented in the Asian Houbara and both subspecies of Great Bustard (Steich et al. 2006, Combreau et al. 2011, M. Kessler unpubl. data). The interannual variation in these movements may increase the risk of collision by taking birds into unfamiliar landscapes (Bernardino et al. 2018).

**Recommendations for mitigating powerline impacts on bustards**

In the planning of new powerlines and the retrofitting (upgrading) of existing ones it is important first to identify the measures necessary to avoid or reduce any impacts on bustards, and only then to offset the residual impacts (Ekstrom et al. 2015). Early evaluation of the risks posed by the projects and the design of effective mitigation strategies can help the successful management of the impacts on bustard populations and prevent costly project modifications later. In the following sections recommendations are made based on the available scientific evidence, however some recommendations are expert based and may require additional validation, therefore their application requires careful consideration, depending on local and project specificities.

**Strategic planning and line routing**

In the European Union new powerline projects are largely assessed for their environmental impact on a case-by-case basis (EC 2018). However, project-level decision-making in powerline construction should be guided by strategic planning and assessment of the energy grid at a regional and national scale, to avoid redundancy and reduce the number of lines (D’Amico et al. 2018, EC 2018). Sensitivity maps and collision risk models (e.g. based on telemetry data) are key tools in identifying existing hazardous areas within the grid or critical ‘no-go’ areas for new energy developments and associated powerlines (Combreau et al. 2011, Silva et al. 2014, Allinson et al. 2020). Electricity grid managers and planning authorities should therefore collect all relevant information on the temporal and spatial use of landscapes by species of conservation concern at a national or regional scale in order to enable sound decision-making to proceed.

To avoid conflicts, particularly in key bustard conservation areas, powerlines may be avoided altogether. In some contexts (e.g. low-voltage lines in rural areas), it is now possible to use microgeneration technologies to produce energy independently from centralised grid-connected power. Numerous solutions are available, principally involving solar or wind energy or both combined; they are robust, easy to install and modular in structure, aiming for low carbon footprints and cost reduction (Balcombe et al. 2014).

When the construction of powerlines is inevitable, optimal routing (in terms of smallest impact on bustards) is critical. It should be based on a careful evaluation of the area’s ecological characteristics, and of existing infrastructures or activities that may already affect local bustard populations. Adding new circuits to existing infrastructure is generally preferable, because it avoids impacting new areas and provides an opportunity to make the existing infrastructure safer for birds (APLIC 2012, SNH 2016). However, if a completely new powerline is unavoidable, running it parallel to existing linear structures such as roads and railways, which bustards already avoid, may be expected to limit the damage (Torres et al. 2011, Malo et al. 2017, Shaw et al. 2018). Even so, when a new powerline is installed parallel to an existing unmarked line it is advisable to retrofit the latter by installing line-marking devices (see ‘Line marking’ below) and to stagger the pylons so that, as much as possible, the pylons of one line are placed next to the mid-span of the other line (Pallett et al. 2022).

Nevertheless, the best ways to prevent collision events and displacement/barrier effects are either through underground cabling (see ‘Line undergrounding’ below) or by routing the line far away both from high-quality bustard habitats (Silva et al. 2010, Lóránt and Vadász 2014, Marques et al. 2020, 2021) and from bustard migratory routes and stopover sites (Raab et al. 2011, Palacin et al. 2017, Alonso et al. 2020). Avoiding migration areas is, however, a challenge for long-distance migrant bustard populations, because they show inter-individual and inter-annual variation in their migratory routes, stopovers and wintering sites (Combreau et al. 2011, Kessler et al. 2013, Burnside et al. 2020). It may also be a challenge when species (e.g. Ludwig’s Bustard) are nomadic in arid environments (Shaw et al. 2018).
Line undergrounding

Burying cables necessarily eliminates bird collisions. Undergrounding is therefore the only option if a bustard population is to be certain to survive the threat from a new or existing powerline (e.g. Raab et al. 2012). Undergrounding powerlines improves supply reliability, aesthetic appearance, and worker and public safety, while reducing liability expenses due to wildfires arising from downed lines (Brundy 2019). However, it entails financial, technical, environmental and legal challenges (Antal 2010, Brockbank 2014).

Undergrounding demands a high initial outlay, particularly for transmission lines (Parsons Brinckerhoff 2012, Teegala and Singal 2015), albeit lower for distribution lines (Hall 2013). In the longer term, however, undergrounding can reduce the operational and maintenance costs for distribution lines and improve reliability owing to fewer outages (Fenrick and Getachew 2012, Glass and Glass 2019). Over the lifetime of a distribution cable, undergrounding appears cost-effective and is becoming standard practice in several European countries (Haas et al. 2005, Raab et al. 2012); it is also increasingly used in parts of the United States to reduce the risk of wildfires (Hall 2013). Although technically and financially more challenging, the burial of high-voltage (i.e. over 110 kV) transmission lines has been undertaken where they bisect areas of high natural value (Prinsen et al. 2012) and should not be discarded in critical areas for bustards.

Line design and construction

If the construction of an overhead line across a landscape used by bustards cannot be avoided, collision risk must be minimised. This requires decisions on the exact location of the pylons and their configuration, based on the line features known to reduce collision risk for birds generally and suspected of doing so for bustards in particular. Cables should run as low as possible, because bustards fly at fairly low altitudes and tend to cross powerlines over the cables rather than between or below them (Neves et al. 2005, Marques et al. 2007, 2021). Bustards evidently see and avoid pylons, and most collisions occur in the middle of the span (Anderson 2002, Neves et al. 2005, Shaw 2013, Pallett et al. 2022). Thus, in powerlines with typically very long spans (e.g. transmission lines), decreasing inter-pylon distances allows lower line heights and simultaneously reduces the length of the middle section of the spans, which should accordingly reduce bustard collision risk. Moreover, the obstruction of vertical airspace should be minimised by arranging the conductors horizontally (Figure S3; Shaw et al. 2018, Marques et al. 2021). The use of earth wires, which, being thinner and thus less visible, pose greater risks to all birds (e.g. Bevanger and Broseth 2001), should be avoided whenever possible.

Thicker cables and bundled conductors, with as many ‘spacers’ as possible, are expected to increase line visibility and reduce bustard collisions. Thus, a further possible mitigation measure, for use at least on medium-voltage powerlines, is the ‘spacer cable’, which was developed to reduce power outages caused by contacts of lines with trees (Ramirez-Vazquez and Espino-Cortes 2012). This technology uses insulated cables, which allow the conductors to be positioned closer to each other than is possible with bare wires on crossarms. Spacer cables could reduce the risk of collision both by decreasing the total vertical height of the powerline assemblage and by making the conductors more visible. Research into the wider use of spacer cables would help determine the feasibility of their roll-out at least in the most urgent situations. To minimise bustard disturbance, line construction and maintenance times should be as short as possible and undertaken outside the breeding season (Nagy 2009, Sastre et al. 2009).

Line marking

Line marking with BFDs is the commonest measure used around the world to reduce bird collisions with powerlines (Figure 2; reviewed, along with other mitigation strategies, in APLIC 2012, Bernardino et al. 2018). BFDs exist in a wide range of forms, but fall into two main categories: static and dynamic. Static devices, typically in the form of small- to large-diameter PVC spirals of different colours, are wrapped around the wires and have no moving parts. Dynamic BFDs devices (also called ‘flappers’; Figure S2) are variously shaped like plates, discs, crossed bands or strips (e.g. RIBE diverters), and usually hang from the wire via a clamp which allows the wind to move them. These devices have greatly evolved over the years in terms of materials (e.g. incorporation of reflective and/or luminescent parts) and dynamic features (e.g. swinging or rotating plates), based on the assumption that moving objects are more likely to be detected by flying birds than static ones (Martin 2011). This assumption may perhaps be mistaken in the case of bustards, as visual field studies suggest that they have poor forward vision in flight (Martin and Shaw 2010). Moreover, dynamic BFDs (particularly those with rotating features) may exhibit high malfunction rates (Sporer et al. 2013, Dashnyam et al. 2016), although...
manufacturers have recently endeavoured to increase their quality, with some models already showing relatively good long-term performance (Shaw et al. 2021).

To date, experiments show that BFDs reduce overall bird collision rates with powerlines, on average, by half (Bernardino et al. 2019), but their effectiveness is highly variable depending on the site, target species and BFD type; and with bustards the evidence is discouragingly weak, or finds no effect. Two studies reported significant but slight positive effects of static ‘spiral’ BFDs for the Little Bustard, the smallest (but not the lightest) species of bustard, which is expected to fly more slowly than larger species (Barrientos et al. 2012, Marques et al. 2021). The first of these studies also found that in the far heavier and less manoeuvrable Great Bustard collisions decreased significantly (if slightly) when lines were marked with the larger (and therefore sooner seen) of two ‘spiral’ diverters (Barrientos et al. 2012). However, a simultaneous study somewhat contradictorily found that dynamic ‘firefly’ BFDs significantly reduced the collision rates of Little and Great Bustards combined, while large spirals and ‘crossed band’ dynamic BFDs did not (Estanque et al. 2012; see Figure S2 for images of BFD type). In stronger contrast, studies in the Iberian peninsula and Canary Islands either found no significant effect of line marking on bustard collision rates (Janss and Ferrer 1998, Marques et al. 2007) or were inconclusive owing to low sample sizes (Alonso et al. 1994, Lorenzo and Cabrera 2009, Infante 2011). Troublingly, the most comprehensive study to date to assess the effectiveness of BFDs on bustards, undertaken in South Africa over an eight-year period and using a Before-After Control-Impact design, found that large spirals and ‘flappers’ (in the form of discs) had no significant effect on the collision rates of bustards, including smaller species (Shaw et al. 2021). Aviation spheres have produced (to some extent) reductions in mortality for other large birds, such was the case of a study with Sandhill Cranes Antigone canadensis that showed a 56% of collision reduction (Morkill and Anderson 1991), but their effects for bustards are not yet studied (Murphy et al. 2016a; review in APLIC 2012).

These findings present a serious challenge, as wire-marking seems insufficient to prevent powerlines from causing irreparable damage to bustard populations over time. Nevertheless, we regard the marking of new or existing powerlines as mandatory, partly because, when there is scientific uncertainty and until the marking of new or existing powerlines as mandatory, partly damage to bustard populations over time. Nevertheless, we regard seems insufficient to prevent powerlines from causing irreparable

2012).

Further product development of BFDs, involving size, shape, dynamism, lights (e.g. LEDs and lasers), colours and reflectiveness, is necessary in collaboration with avian ecologists, sensory biologists and powerline engineers to better match the sensory ecology of bustards. Although near-ultraviolet wavelength lights have been used to reduce twilight collisions for cranes arriving at roost sites (Dwyer et al. 2019), the visual pigment opsin sequence (NCBI Reference Sequence: XP_010124621.1) and large eye size of bustards indicate their limited ultraviolet-sensitivity (Ödeen et al. 2009, Lind et al. 2014). Research is required to determine the most salient wavelengths for bustards’ visual systems and, among those, the frequencies that provide maximum contrast to environmental light. The development of acoustic deterrents, or visual deterrents which fall better within the line of sight of bustards (such as ground-mounted lights), may also be productive (Boycott et al. 2021).

Habitat management

Habitat management could potentially be used to reduce bustard collision risk with powerlines or, as a last resort, to compensate for bustard collision mortality. Restricting anthropogenic disturbance (e.g. from hunting, recreation) close to powerlines could reduce collisions resulting from bustards flushed into flight (Sastre et al. 2009). Lessening the attractiveness of the habitat near lines and/or creating attractive habitats further away might also contribute to lower collision rates. Such measures, however, have never been tested and would require habitat modification on a large scale.

Compensation for powerline mortalities could involve measures such as promoting bustard-friendly habitat management, giving full protection to other bustard sites, and reducing disturbance at display and nesting sites (Bretagnolle et al. 2011, Raab et al. 2014, Jhala et al. 2020). To achieve long-term success, however, these actions should be species-specific, informed by rigorous research, and carefully planned with local stakeholders (e.g. farmers, NGOs). Such interventions should enhance the affected bustard populations to the point where they are measurably stronger than before.

With the current uncertainty over BFD effectiveness, compensation measures must be considered mandatory when new powerline projects threaten bustard populations. Typically, compensation is assessed on a case-by-case basis, but the cumulative impact of the existing energy grid should urgently be assessed. Powerline companies are responsible for the overall impacts that their infrastructures have on biodiversity, and should therefore assess and duly implement, to the full (encompassing the lifetime
of the line), the interventions necessary to compensate for bustard mortalities and displacement.

**Recommendations for monitoring impacts and mitigation effectiveness**

Powerline monitoring schemes for bustards are crucial for three main purposes: (i) to determine collision mortality rates; (ii) to assess displacement and barrier effects caused by the infrastructure; and (iii) to evaluate the effectiveness of mitigation measures implemented.

**Determining mortality rates**

**Carcass searches**

Carcass searches under powerlines are the most common method for determining mortality rates and displacement and barrier effects caused by the infrastructure. Carcass searches should include (i) a survey of locations where bustard species are resident or else synchronised with their seasonal presence; (ii) a search of the area along the line (to detect seasonal variations), but preferably last for 2–3 years. Decisions on subsequent monitoring should be based on results obtained.

**Bias corrections**

The number of carcasses found during surveys is only a proportion of the true mortalities, because some deaths will not be registered owing to removal bias (carcasses sequestered by scavengers or reduced by decomposition), detection bias (carcasses missed through visibility issues) and crippling bias (fatally injured birds flying or walking beyond the search area). Carcass removal and detection rates vary greatly among study sites (Barrientos et al. 2018, Bernardino et al. 2022), so in order to estimate true collision rates as accurately as possible, field trials to ascertain the relevant bias-correction factors are essential.

**Carcass removal trials** should be undertaken at least in the first year of post-construction monitoring, at every relevant season. At least 10 (and preferably 20) bird carcasses (matching the size and, if possible, coloration of the target species) are needed per season (Bispo et al. 2015). They should be distributed widely, evenly, and proportionately across the different powerline sections regularly searched for bird fatalities. Once placed, they should initially be checked daily and then at increasing intervals (e.g. daily up to day 4, then on day 7, 14, 21 and 28), to determine their persistence probability over time (Schutgens et al. 2014, Bispo et al. 2015).

**Carcass detection trials** may be carried out using the same carcasses as in the removal trials but ideally also feather spots (Stevens et al. 2011, Reyes et al. 2016). These trials can be undertaken during scheduled carcass searches, without prior knowledge of the searches. All carcasses not detected by individual searchers or search teams should be promptly checked to confirm the persistence of the carcasses or their remains (to exclude trial errors due to rapid removal by scavengers). Trials should be repeated in two or more relevant seasons to account for differences in visibility (depending on vegetation cover and height) and, consequently, in detection probabilities of carcasses and feather spots over time (Stevens et al. 2011).

**Crippling bias** (the proportion of birds colliding with a line that fall or die outside the survey strip) remains an important knowledge gap, although it strongly influences mortality estimates (Rioux et al. 2013). This bias is extremely difficult to gather data on and, hence, unlikely to be determined under standard monitoring programmes. Moreover, the few studies investigating this bias reported such a wide range of values, between 20% and 82% (Bévanger 1995, Rioux et al. 2013, Murphy et al. 2016b, Travers et al. 2021), that their use is inappropriate. Thus, until further data are available, we suggest not to adjust mortality estimates for crippling bias, and researchers should accept that, for now, the estimated mortality rates correspond to the minimum expected. When studies do adjust for crippling bias they should clearly state the correction value used.

**Mortality estimators**

Apart from producing observed fatality rates (based solely on carcass searches), bustard carcass counts should be adjusted for removal, detection and, if measured, crippling bias. Several mortality estimators are available but, currently, GenEst estimator (Dalthorp et al. 2018) incorporates the best features of previous estimators and is able to account for uncertainty in the final mortality estimates. In case of rare mortality events, alternative estimation approaches (e.g. Huso et al. 2015) should be considered.
Assessing displacement and barrier effects

The study of displacement effects is feasible and valuable where bustards occur at a high enough density. Ideally, monitoring should be based on a Before-After gradient (BAG) approach, where the abundance of a given bustard species is characterised at varying distances from the powerline before and after its construction (Powell et al. 2017). Bird surveys should ideally cover at least a complete year cycle before the line is constructed, so that the full effect of the infrastructure can be measured. If the line already exists, a gradient approach (’impact gradient’, IG) can still be used, quantifying abundance as a function of distance to the infrastructure, but all other confounding effects (e.g. habitat, other sources of disturbance) must be taken into account.

Any expected barrier effects should be monitored by comparing flight paths and line-crossing rates (obtained by direct observations) before and after the powerline is built. If the line is already installed, other indirect methods based on the IG approach can be considered, such as recording take-off directions at different distances to the line (Raab et al. 2011).

Besides direct observations, both displacement and barrier effects may be assessed through bird-tracking technologies (e.g. satellite/GPS telemetry) which provide high spatial and temporal resolution data on bird movements (Pruett et al. 2009).

Evaluating mitigation measures

It is vital to evaluate the performance of mitigation measures, particularly line marking, in reducing bustard mortality. For existing retrofitted powerlines a Before-After Control-Impact (BACI) approach should ideally be implemented in which mortality is quantified for marked and unmarked sections of line, both before and after marking (e.g. Shaw et al. 2021). For new powerlines (when BFDs are installed at the construction stage) the monitoring approach must be the simple Control-Impact (CI), where mortality is assessed on marked versus unmarked sections of line. However, for a true comparison, bias correction experiments (see above) have to be undertaken in both sections, which might have, e.g., different habitats, scavenger populations and bustard abundances (Bernardino et al. 2019). Additionally, bustard crossing rates (which can be used as a proxy of local abundance) should be determined for the marked and unmarked sections and then used to adjust/calibrate the respective estimated mortality rates (Mercker and Jödicke 2021).

Additional key issues

Local and regional bustard populations require constant monitoring so that additional mitigation and/or compensation measures can be implemented promptly in response to any demographic changes detected. The long-term threat posed by powerlines to bustard populations may be assessed through population viability analysis (e.g. Uddin et al. 2021). It must, however, be based on robust mortality and demographic data (e.g. population size, social structure, reproduction parameters), so further basic population monitoring is needed to generate such data, particularly for threatened species. Assessments of bustard population dynamics should also consider the cumulative impacts of powerlines within their range, and impacts from other nearby structures (e.g. roads, windfarms). Long-term tracking projects, robustly sampling individually marked birds, can provide a reliable estimate of mortality rates caused by collisions with powerlines in the context of other anthropogenic sources of bustard mortality (Table 1; Palacín et al. 2017, Marcelino et al. 2018).

Reflections and conclusions

Of the 14 bustard species documented here as having suffered powerline mortality three have the IUCN Red List category 'Critically Endangered', two are 'Endangered', four 'Vulnerable', four 'Near Threatened' and only two 'Least Concern' (Table 1). Ethically, therefore, it may be questionable to experiment with the use or non-use of various mitigation measures and designs in order to assess which are effective in preventing collisions in species that are at elevated risk of extinction. Equally, however, the lack of solid information and certainty over the scale of the problem, and over the efficacy of the measures intended to address it, leaves conservationists in the unenviable position of taking crucial decisions in an information environment dominated by anecdote. It is an ironic reflection of this circumstance that the ‘Critically Endangered’ Bengal Florican Houbaraopsis bengalensis was recently—and emphatically—identified as at serious risk from a new powerline in Cambodia (Mahood et al. 2016) at a time when it had not yet been recorded as a powerline victim.

Anecdote can of course be instructive, revealing for example that a small, medium-tension powerline consisting of three horizontally aligned wires can cause repeated fatalities to a bird the size and weight (up to 19 kg) of a Kori Bustard (Collar 2019). Nevertheless, this first global review of the problem of bustard mortalities at powerlines seeks to combine anecdote with quantified analyses to provide as robust a body of evidence as possible while still necessarily invoking the precautionary principle to govern management responses. Data on bird collisions are difficult and expensive to obtain and to compare; the proposed guidelines encourage conservationists and researchers to collect data in a systematic way and enable interdisciplinary studies to better understand powerline impacts and to use and develop effective mitigation measures. An important need, therefore, is for conservationists to establish and inform relevant authorities of the distribution and numbers of bustards within their areas of concern, so as to forestall proposals for powerlines that would affect the areas on which the birds depend.

Additional risks are imposed if the landscapes in question are allowed to be fragmented by fences and criss-crossed by telephone and rail lines (both of which are also hazardous for bustards: Table S2) or repurposed for wind-turbines and principally solar farms, which may not kill birds outright but will lead in most cases to extensive habitat loss and disruption as well as to the expansion of electricity grids. Vigilance on these other issues is equally necessary. Nevertheless, an important further strategy for conservationists to pursue is engagement with energy companies. Energy delivery is one essential public good; nature conservation is another. When energy companies are reduced to vilifying conservation for obstructing their plans, as happened following the April 2021 Indian Supreme Court order to bury all powerlines affecting the survival of the Great Indian Bustard (The Economic Times 2021), the balance of those public goods has been lost.

Restoring that balance will also necessarily involve restoring real balances in nature, with energy companies obliged and, better, voluntarily agreeing to compensate fully for the negative impacts their powerlines have on bustards. Compensation should primarily be channelled towards increasing productivity in accordance with the level of mortality caused by the powerline. Additional research
is needed, however, to attain a more holistic understanding of the cumulative impacts of the electric grids on bustard demography and overall impact on populations, particularly for those more threatened species. With greater appreciation of each other’s interests and needs, however, fruitful partnerships can emerge, as in South Africa, Namibia, and Portugal where conservationists and academia are working closely with the national power suppliers to find sound and equitable solutions to the bustard/powerline conflict.

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