Wildlife Society Bulletin 1–8; 2019; DOI: 10.1002/wsb.990

Original Article

Mitigation Techniques to Reduce Avian Electrocution Rates

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ABSTRACT From August 2013, we undertook a 1-year trial of mitigation techniques at an electricity power line in the Mongolian steppe with a high avian electrocution rate. We examined 2 mitigation methods at phase-1 conductors on the top of power poles (i.e., reconfiguration of the insulator mount and insulation covers on the conductor wire) and 3 mitigation methods at phase-2 and 3 conductors on pole cross-arms (i.e., perch deflector brushes, rotating-mirror perch deterrents, and insulation covers on the conductor wires). The perch management techniques selected for the trial are currently widely adopted by power line managers in Mongolia. In comparison with the control, with no mitigation, electrocution rates were reduced both by the reconfiguration of insulator mounts and insulation of conductor wires at phase-1, though the reduction was greater for the former—73% mean reduction for reconfigured mounts and 59% for insulation covers. Electrocution rates were reduced by the placement of rotating-mirrors and insulation of conductor wires at phases 2 and 3, with the reduction being greater for the former—91% mean reduction for mirrors and 66% for insulation covers. Deployment of metal perch deflector brushes at phases 2 and 3 had no effect on electrocution rates and should not be used as mitigation. Most electrocutions occurred at phase 1 on the top of the pole, indicating that mitigation should be prioritized at this phase. In terms of cost and efficacy, reconfigured mounts represented the best option as a permanent fix at phase 1. At phases on cross-arms, the relative merits of mirrors and insulation covers need to be assessed over a longer period, and these temporary mitigation measures should be compared with alternative permanent fixes.

KEY WORDS avian electrocution, bird of prey, deterrent, insulation, mitigation, Mongolia, perch deflector.

Large birds of prey that use power lines for perching are highly susceptible to electrocution (Bevanger 1994, Lehman et al. 2007). Electrocution of birds at power lines is a long-standing and widespread phenomenon, affecting numerous avian species across several continents including Africa (Ledger and Annegarn 1981, Jenkins et al. 2010, Angelov et al. 2013), the Americas (Lehman et al. 2010, Kemper et al. 2013, Dwyer et al. 2014), Asia (Dixon et al. 2013, Harness et al. 2013), Australasia (Fox and Wynn 2010), and Europe (Ferrer et al. 1991, Tintó et al. 2010). High levels of mortality combined with the unfavorable conservation status of certain raptors species means that electrocution has the potential to have a major impact on the population of certain species (Hernández-Matías et al. 2015). The issue of avian electrocution has been the focus of attention for conservationists internationally, resulting in the Convention on the Conservation of Migratory Species of Wild Animals adopting guidelines on how to prevent birds being killed by power line electrocutions (Prinsen et al. 2011, 2012).

Electrocution occurs primarily at low- and medium-voltage power distribution lines (≤60 kV) and occurs when birds, mostly larger species, contact 2 conductor wires or 1 wire and a grounded part of the power pole simultaneously (APLIC 2006, Prinsen et al. 2011). A wide range of mitigation methods are available, yet data on their relative efficacy are surprisingly limited (Bevanger 1994, Negro and Ferrer 1995, Janss and Ferrer 1999, Prinsen et al. 2012).

Received: 11 September 2018; Accepted: 25 March 2019
Published:

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Few studies are available that allow a statistical comparison of mitigation measures between species and areas (APLIC 2006, Jenkins et al. 2010, Barrientos et al. 2011). Dwyer et al. (2016) experimentally examined the influence of deflectors on power-pole perching behavior of raptors in captivity. Tintó et al. (2010) used multivariate modelling to demonstrate that mitigation had been effectively implemented at a landscape scale in Spain. Similarly, retrofitting mitigation reduced mortality for the endangered Bonelli's eagle (*Aquila fasciata*) in France (Chevallier et al. 2015). Conversely, an extensive Spanish study found that power poles with cable insulation fitted retrospectively—a widely used and recommended mitigation procedure—had greater levels of electrocution than untreated poles (Guil et al. 2011).

Mitigation can take many forms and specific designs vary according to manufacturer (Ferrer 2012, Prinsen et al. 2012, APLIC 2016). A common method of mitigation is the installation of insulation covers over the energized conductor cables or over nonenergized perching sites (such as cross-arms). Alternative mitigation includes using deflector devices (such as spikes and brushes) to physically prevent birds from using specific perch locations or to use deterrent devices (such as rotating mirrors) to deter them from perching at all. Mitigation typically involves adding a component to the base configuration of a pole, which often entails additional maintenance costs. In contrast, remediation involves altering the base configuration of power poles to reduce electrocution risk.

Previous studies in Mongolia have identified the problem of electrocution as a conservation issue for raptors (Harness et al. 2008, Dixon 2010, Purevdorj and Sundev 2012), quantified electrocution rates and the scale of the problem (Dixon et al. 2013, Dixon 2016), identified factors influencing electrocution rates (Dixon et al. 2017), and assessed the efficacy of mitigation techniques to reduce them (Dixon et al. 2018). Reported electrocution rates of raptors in Mongolia are extremely high because the open steppe landscape is devoid of alternative elevated perches and supports an abundance of small mammal prey whose population densities fluctuate temporally and spatially. High densities of small mammals can attract large aggregations of raptors, especially during the postfledging dispersal period; raptor electrocution rates are maximized where dangerous power lines coincide with these aggregations (Dixon 2016). Our goal was to assess the efficacy of different forms of mitigation aimed at reducing electrocution rates at a power line in the Mongolian steppe that was known *a priori* to kill large number of birds of prey (estimated 24–45/month; Dixon et al. 2013). We assessed efficacy of techniques currently adopted by power line managers in Mongolia (i.e., brush-type perch deflectors and rotating mirror perch deterrents on cross-arms; A. Dixon, unpublished data), together with additional forms of mitigation. Our experiment also included an assessment of conductor wire insulation and a remediation measure using an alternate design of the pole-top insulator mount. In addition to their efficacy at reducing electrocutions, our experiments allowed us to examine the cost of these different techniques to make a judgement on relative cost-effectiveness.

STUDY AREA

We studied a 3-phase 15-kV line covering 56 km between the district centers of Munkhkhaan (46°58′N 112°2′E) and Uulbayan (46°29′N 112°19′E) in Sukhbaatar province, eastern Mongolia. The line had previously been shown to have a high level of avian electrocution (Dixon et al. 2013). The line had 532 poles, comprising 36 'anchor' poles and 496 'tangent' poles; anchor poles occur at the ends of the line, at deviation points and at intervals (typically 1.5–2.0 km) along straight runs of tangent poles to adjust the strain on conductor wires. All poles were made of grounded steel-reinforced concrete, with grounded steel cross-arms, which meant that any bird that contacted a conductor when perched on either the pole or the cross-arm would be electrocuted. We termed the central conductor wire supported at the top of the poles as phase 1, while the conductor wires that supported either side via the cross-arms of the poles were termed phases 2 and 3. The line traversed undulating and flat, grass-dominated steppe landscape with sparsely vegetated sandy soil. The vegetation was short, being intensively grazed by livestock and the habitat surrounding the line supported high densities of herbivorous small rodents.

METHODS

For the experimental trial, we divided the line into 24 sections of tangent poles between anchor poles, excluding 72 and 42 poles at each end of the line during 2013. We randomly allocated each line section to one of the following treatment groups: 1) phase-1 mount reconfiguration (hereafter called 'mounts'; $n = 5$ sections, 78 poles), 2) phase-1 pin-insulator cap and wire insulation (hereafter called 'covers'; $n = 5$ sections, 80 poles), 3) phase-2 and -3 rotating mirror perch deterrent (hereafter called 'mirrors'; $n = 2$ sections, 33 poles), 4) phase-2 and -3 grounded-steel-brush perch deflector (hereafter called 'brushes'; $n = 2$ sections, 34 poles), 5) phase-2 and -3 covers ($n = 4$ sections, 70 poles), and 6) control with no mitigation deployed ($n = 6$ sections, 98 poles; Table 1). Pole configuration within each of the treatments was identical. We compared electrocution at line sections in each of the treatment groups. We designed the experimental set up to allow us to examine the efficacy of different mitigation methods targeted as specific locations on the power poles; at the top of the pole (phase 1) and on the cross-arm (phases 2 and 3). The number of line sections allocated to each treatment group was determined by our priority to assess the efficacy of mitigation methods not previously adopted in Mongolia (i.e., conductor insulation and an alternative design of pin insulator mount) and further influenced by the number of insulation covers we could purchase for the trial. This resulted in unequal allocation of line sections to the treatment groups—5 sections each for phase-1 covers and phase-1 mounts but only 4 sections for phase-2 and -3 covers, with 6 sections allocated to controls. We divided the remaining 4 line sections between mirrors

Table 1. Summary of mitigation treatments used in an experimental trial at a power line in Sukhbaatar province, Mongolia, during 2013–2014. The 'mount' and 'P1 covers' treatment groups were targeted at electrocution events occurring at phase-1 at the top of the pole, whereas 'P2/3 covers,' 'mirrors,' and 'deflectors' treatment groups were targeted at electrocution events occurring at phases 2 and 3 on the cross-arm.

Treatment Group	Phase-1	Phases 2 and 3	*n* sections	*n* poles
Mount	Arch mount for pin insulator	Upright pin insulators	5	78
P1 Covers	Insulation covers on pin insulator	Upright pin insulators	5	80
P2/3 Covers	Vertical mount for pin insulator	Insulation covers on pin insulators	4	70
Mirrors	Vertical mount for pin insulator	Mirrors, adjacent to pin insulators	2	33
Deflectors	Vertical mount for pin insulator	Deflectors, adjacent to pin insulators	2	34
Control	Vertical mount for pin insulator	Upright pin insulators	6	98

and brushes, the 2 mitigation methods widely adopted in Mongolia.

Reconfiguration of the phase-1 insulator mount at the top of the tangent poles involved replacing the existing vertical, angled steel bracket that was attached to the side of the pole with a new arched steel bracket that passed over the center of the top of the pole (Fig. 1A,B). The intent of this modification was to reposition the pin insulator centrally to prevent raptors from perching at the top of the pole, thus reducing the frequency with which they were exposed to phase-to-ground electrocution risk on phase 1. Insulation of the phase-1 conductor involved fitting them with insulator cap and conductor wire insulation covers, manufactured using a ultraviolet-resistant rigid polymer resin (Fig. 1C; Power Line Sentry LLC, Fort Collins, CO, USA). The intent of this modification was to reduce the possibility that a raptor perching on the pole top could contact the energized conductor. Insulation covers were similarly used at phases 2 and 3 on the cross-arm (Fig. 2A). The rotating mirror perch deterrents and steel brush perch deflectors were manufactured in China and of a similar design to those widely used by power distribution companies across Mongolia (Fig. 2B,C). We affixed mirrors and brushes to the cross-arm at approximately 10 cm from each of the phase-2 and -3 pin insulators. Both types of mitigation present a physical barrier, preventing raptors from perching directly adjacent to the energized conductors on the cross-arm, with the rotating mirror potentially having an additional effect of deterring raptors from perching on the cross-arm, or the pole, at all.

We further included 26 anchor poles in our trial, all of which had previously been reconfigured so that the jumper wires on phases 2 and 3 passed underneath the cross-arm via a suspended insulator rather than above the cross-arm via a pin insulator (Dixon et al. 2017). We fitted an insulator cap and flexible-nylon-hose conductor cover to the phase-1 jumper wires at the top of 8 randomly allocated anchor poles, while the jumper wires connected to pin insulators of the other 18 anchor poles were left uninsulated as controls (Fig. 3; sample size was determined by the number of insulator caps and length of flexible nylon hose we had available for the experimental trial in Mongolia). Each pole was clearly numbered and the mitigation outlined above was fitted to the line by engineers of the Sukhbaatar branch Eastern Electricity Company in early August 2013. To assess the long-term viability of mitigation materials deployed in this study, we recorded the condition of brush perch deflectors, rotating mirror perch deterrents and conductor insulation covers during surveys 2 years (2015) and 5 years (2018) after deployment.

Following an initial clearance of all bird remains from beneath poles, we undertook daily surveys of all poles along the power line from 21 August 2013 to 15 August 2014. Surveys were undertaken alternately by 2 surveyors on motorbike to inspect the area around the base of each pole. The ground below all poles was open and sandy with very sparse grass vegetation, making carcasses highly visible and a low likelihood that any carcasses were not detected. During each survey, surveyors photographed all carcasses of birds

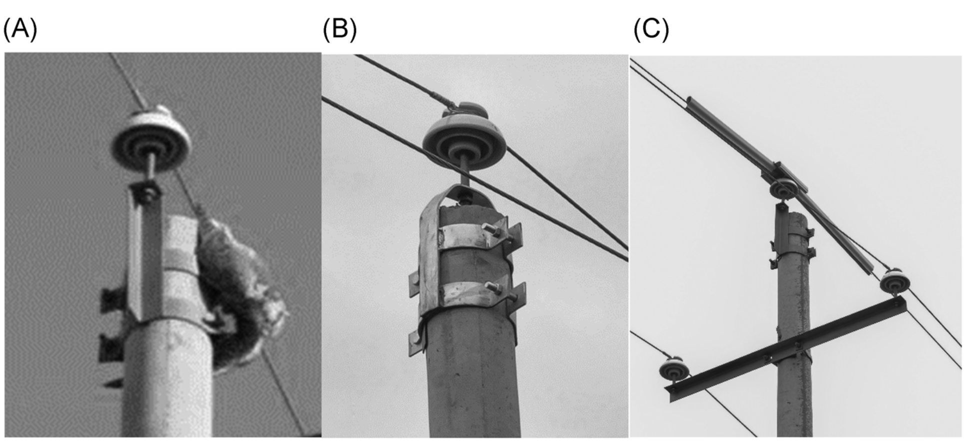

Figure 1. Pole top configurations at the Munkhkhaan-Uulbayan 15 kV electricity distribution line, Sukhbaatar Province, Mongolia in 2013. (A) Standard vertical mount (control) and (B) arch-type mount for pin insulator at phase 1 on top of tangent poles (mount). (C) Insulation cap and covers fitted on phase-1 pin-insulator and conductor cables (P1 covers). Electrocuted Saker Falcon shown in A.

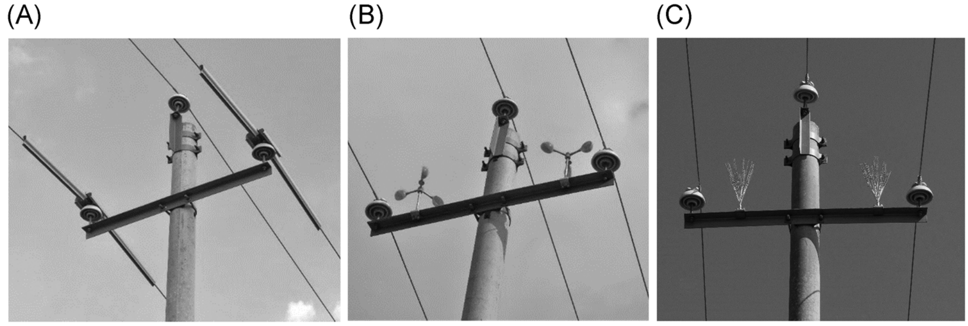

Figure 2. Crossarm configurations at the Munkhkhaan-Uulbayan 15 kV electricity distribution line, Sukhbaatar Province, Mongolia in 2013. (A) Insulation cap and covers fitted on the phase-2 and -3 pin-insulators and conductor cables (P2/3 covers). (B) Rotating mirror perch deterrents fitted to the cross-arm adjacent to the phase-2 and -3 pin insulators (mirrors). (C) Brush perch deflectors fitted to the cross-arm adjacent to the phase-2 and -3 pin insulators (deflectors).

Figure 3. Configuration of jumper wires at anchor poles at the Munkhkhaan-Uulbayan 15 kV electricity distribution line, Sukhbaatar Province, Mongolia in 2013. Pin insulator cover and flexible hose insulation on jumper wire at phase 1 of an anchor pole, where the jumper wires for phases 2 and 3 had been reconfigured to pass under the cross-arm via a suspended insulator.

found below power poles next to a white-board with the date and pole number recorded. Surveyors collected carcasses of saker falcons (*Falco cherrug*), labelled, individually bagged, and stored them in chest-freezers at either end of the power line. Surveyors left carcasses of other species *in situ* with a labelled tape 'flag' attached to one leg for identification during subsequent monitoring visits to ensure none were double-counted. Pathological examination of saker falcon carcasses revealed that all birds died due to electrocution. We have assumed that all other species found freshly dead below the grounded poles died of the same cause.

In June 2012, 2 searchers inventoried the number of small mammal holes that had evidence of current use (hereafter, 'active holes') within a 20-m radius of alternate poles (1,257 m^2; $n = 191$ poles). Active small mammal holes were identified from droppings or tracks at the entrance. We used break-point analysis in the Program R package 'segmented' to define sections of line where hole density differed (Muggeo 2008). Break-point analysis identified 4 spatially discrete sections of line with low ($\bar{x} = 0.8$ holes/pole) or high ($\bar{x} = 6.8$ holes/pole) hole density (Dixon et al. 2017). Line sections were also allocated sequential numbers and each pole was assigned a section number, depending which section it was in on the line; although sections corresponded to treatment groups, we also analyzed them as a distinct category in order to account for any spatial influence on electrocution rates. We used a generalized mixed-effect model (GLMM), with the total number of electrocution events at each tangent pole being the dependent variable, with treatment type considered a fixed factor and mammal hole category and line sections considered as random factors. We used 'nlme' pack within Program R. From the GLMM, we extracted mean estimates of electrocution per pole for each treatment group and calculated their 95% confidence limits from the fitted model mean and standard errors. We computed all analyses using R (R Development Core Team 2013). We used the same GLMM procedure to examine electrocution of birds in 3 different size classes. We classified electrocution victims as small-sized (length ≤35 cm, wingspan ≤70 cm), medium-sized (length 35–75 cm, wingspan 70–160 cm), and large-sized (length >75 cm, wingspan >160 cm) based on published data for the species (del Hoyo et al. 2014). We analyzed the efficacy of mitigation at anchor poles taking poles where electrocution occurred as the sampling unit using Fisher's exact test in a 2×2 contingency table.

RESULTS

We recorded 407 electrocuted avian carcasses at the 393 tangent poles in the 24 line sections within our 6 treatment groups (Table 2). We recorded 36 small-sized birds (common kestrel [*Falco tinnunculus*], $n = 32$; chough [*Pyrrhocorax pyrrhocorax*], $n = 3$; hoopoe [*Upupa epops*], $n = 1$), 359 medium-sized birds (saker falcon, $n = 180$; upland buzzard [*Buteo hemilasius*] and common buzzard [*Buteo buteo*], $n = 148$; raven [*Corvus corax*], $n = 28$; black kite [*Milvus migrans*], $n = 1$; goshawk [*Accipiter gentilis*], $n = 1$; Ural owl [*Strix uralensis*], $n = 1$), and 12 large-sized birds (steppe eagle [*Aquila nipalensis*] and golden eagle [*A. chrysaetos*], $n = 10$; eagle owl [*Bubo bubo*], $n = 2$). Only one large-sized bird, an eagle owl, was electrocuted on a pole with mitigation at phases 2 and 3, but there was no difference in electrocution rates among different treatment groups for large- and small-sized birds, but sample sizes were small. However, in comparison with controls, medium-sized birds had lower electrocution rates at phase-1 conductors at the tops of poles with mounts ($t_{252} = -4.93$, $P < 0.001$) and covers ($t_{252} = -3.17$, $P < 0.001$), and phase-2 and -3 conductors on the cross-arms with mirrors ($t_{232} = -4.11$, $P < 0.001$) and covers ($t_{232} = -3.59$, $P < 0.001$).

At phase-1 conductors on the top of the pole, there were fewer electrocutions at poles with mounts and covers than at poles in the control group (Table 3). The mean electrocution rate for a tangent pole in the control group was 1.5 birds/annum (95% CI = 1.0–2.0), whereas the electrocution rate for poles with mounts was 0.4 birds/annum (95% CI = 0.2–0.7). For poles with the conductor insulation covers it was 0.5 birds/annum (95% CI = 0.3–1.0). There was a difference in the efficacy of mounts in comparison with covers ($t_{155} = -2.45$, $P = 0.02$), with a mean reduction of 73% and 59% for these 2 mitigation methods, respectively, in comparison with the control group (Fig. 4).

At phase-2 and -3 conductors on the cross-arms, there were fewer electrocutions at poles with mirrors and covers than at poles in the control group; there was no difference for poles with brush deflectors (Table 2). The electrocution rate for poles with the mirrors was 0.2 birds/annum (95% CI = 0.1–0.5), for poles with the covers it was 0.5 birds/annum (95% CI = 0.3–0.9), and for those with brush deflectors it was 1.2 birds/annum (95% CI = 0.5–2.7). There was a difference in the efficacy of mirrors in comparison with covers ($t_{101} = -2.95$, $P = 0.003$), with a mean reduction of 91% and 66% for these 2 mitigation methods, respectively, in comparison with the control group (Fig. 4).

Small mammal holes were associated with electrocution, with the frequency of events being greatest at poles categorized as having a high density of active holes in the vicinity ($t_{386} = -5.31$, $P < 0.001$). Electrocution of 13 birds occurred at 7 (39%) of the 18 anchor poles without insulation of the phase-1 jumper wires, but only 1 bird was electrocuted at 1 (13%) of 8 anchor poles with covers. It is noteworthy that electrocution occurred at 12 (60%) of the 20 uninsulated anchor poles in line sections categorized as having a high density of small mammal holes, whereas electrocution occurred at only 1 (17%) of 6 anchor poles in line sections with a low density of small mammal holes. This difference was not significant, but our sample size was small (Fisher's exact test, $P = 0.36$).

Two years after deployment, 16 rotating-mirror units were missing having become detached from cross-arms (24%); of the remaining 50, 47 were whole and rotating (94%), and 3 were broken and static (6%). All other forms of mitigation remained in place 2 years after deployment. After 5 years of deployment, 18 rotating-mirror units had become detached from cross-arms (27%); of the 48 remaining, 35 were whole and rotating (73%), 5 were whole but static (10%), and 8 were broken and static (17%). After 5 years, all brush deflectors remained in place; only 1 of the 213 insulation covers had fallen off.

Table 2. Number of annual electrocutions per pole (*n*) for small, medium, and large-sized birds in each treatment of the experimental trial at a power line in Sukhbaatar, Mongolia, during 2013–2014.

Treatment	Small	Medium	Large
Control	0.10 (10)	1.43 (140)	0.02 (2)
Phase-1 covers	0.09 (7)	0.84 (67)	0.06 (5)
Phase-1 mounts	0.04 (3)	0.58 (45)	0.05 (4)
Phases 2 and 3 covers	0.11 (8)	0.69 (48)	0.00
Phases 2 and 3 mirrors	0.03 (1)	0.18 (6)	0.00
Phases 2 and 3 deflectors	0.21 (7)	1.53 (53)	0.03 (1)

DISCUSSION

Insulation of live conductor wires and covers for upright pin insulators reduced electrocution rates at all 3 phases on tangent poles, and fewer electrocutions occurred when insulation was applied to jumper wires on anchor poles. This form of mitigation was the only treatment that could be applied to all 3 phases. However, at phase 1 at the top of the pole, alternative pin insulator mounts achieved greater reductions in electrocution than insulation covers, as did

Table 3. Electrocution rates among different treatment groups during experimental trial conducted in 2013–14 at the Munkhkhaan-Uulbayan 15 kV electricity distribution line in Sukhbaatar Province, Mongolia. The generalized mixed-effect model compared the number of electrocution events at each pole (dependent variable) in relation to the treatment type (fixed variable), accounting for the influence of mammal holes and sequential line sections (random factors). Parameter estimates of model[a] in relation to the control with standard errors, *t*-test values and significance.

Treatment	Estimates	SE	*t*	*P*
Phase-1 covers	−0.44	0.15	−3.92	<0.001
Phase-1 mounts	−0.86	0.17	−5.57	<0.001
Phases 2 and 3 covers	−0.63	0.17	−4.13	<0.001
Phases 2 and 3 mirrors	−1.99	0.43	−5.45	<0.001
Phases 2 and 3 deflectors	0.10	0.17	0.59	0.55

[a] Model dispersion is indicated by null deviance = 588.8, df = 392; and residual deviance = 506.1, df = 387.

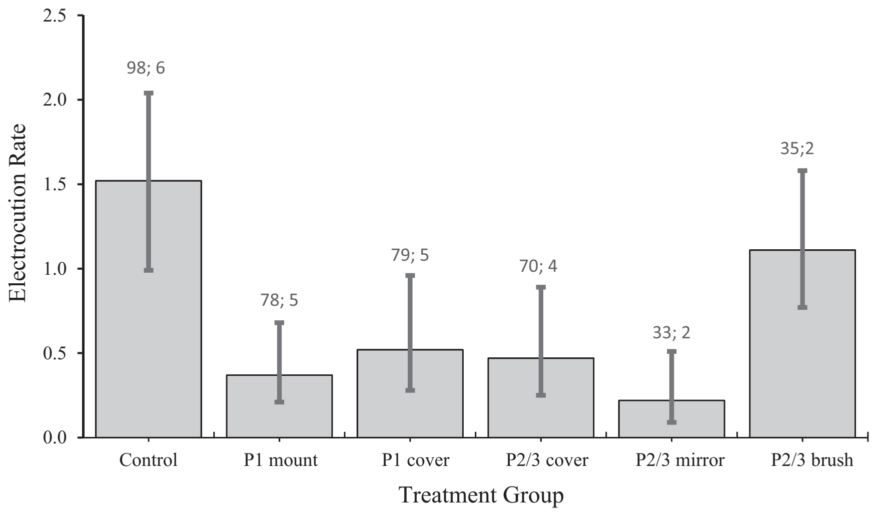

Figure 4. Electrocution rates at the Munkhkhaan-Uulbayan 15 kV electricity distribution line, Sukhbaatar Province, Mongolia during the experimental trial 2013-14. Electrocution rate expressed as the mean number of carcasses per pole per annum for each treatment group in the trial: P1 = phase 1 at the top of the pole, P2/3 = phases 2 and 3 at the ends of the cross-arm, mount = arch-type pin insulator mount, cover = insulation cover for pin insulator and conductor wire, mirror = rotating mirror perch deterrent, and brush = brush perch deflector. Bars indicate 95% confidence intervals, values above bars represent number of poles; number of line sections in each treatment group.

rotating mirrors deployed on cross-arms at phases 2 and 3. At phase 1 on the top of the pole, the mount operates as a perch deflector by preventing birds using the top of the concrete pole as a perch site; instead birds can only perch on top of the pin insulator or on the cross-arm below. These covers operate by preventing direct contact between the live conductor cable and a grounded bird perched on the top of the concrete pole: they may also have a deflector effect in causing birds that might otherwise perch on top of the pin insulator, or the top of the pole, to use the lower cross-arm instead, where they are susceptible to electrocution. It is possible that a deflector effect accounts for the difference in electrocution rates observed between mounts and covers at phase 1. However, evidence of a deflector effect would need to be addressed via observations, such as that conducted by Dwyer and Doloughan (2014) to quantify perch frequency at various locations on the pole top.

Mitigation involving changing the insulator mount at phase 1 reduced electrocution rates by 73% compared with control poles, indicating that most electrocution events occurred on the top of the pole at phase 1; a 73% reduction suggests that nearly 3 in 4 electrocution events occurred at phase 1. This concurs with the findings of Dwyer et al. (2016), who reported raptors selectively perched on pole tops compared with cross-arms. Consequently, mitigation targeted at the pole top can potentially be more effective than targeting phases on the cross-arms, which is currently the most prevalent strategy employed by line managers in Mongolia.

At phases 2 and 3 on the cross-arm, covers prevent a bird perched on the cross-arm adjacent to the pin insulator from coming into contact with the live conductors. They also may have a deflector effect discouraging birds from perching on, or adjacent to, the pin insulator. Mirrors can operate as perch deterrents and additionally, when positioned adjacent to pin insulators, may discourage birds from perching on the cross-arm directly next to the live conductors or anywhere on the pole. In our trial, at different sections of the line, there were poles without mirrors that birds could use as alternative perches, which would not be the case if all poles on the line were deployed with mirrors; it is not certain that mirrors would be such an effective deterrent under this scenario. In addition, mirrors can fail over time by breaking off or ceasing to rotate, thereby requiring regular replacement. Furthermore, there is also the possibility that some birds could become habituated to mirrors over longer time periods, as is the case with a range of bird deterrent methods (Bishop et al. 2003, Avery and Werner 2017). Brushes have a similar deflector effect but do not prevent birds from perching on top of the pin insulator. Brushes, despite being widely used as perch deflectors at power lines in Mongolia, did not reduce electrocution rates and may even have increased them, probably because birds perched on the pin insulators can simultaneously contact the live conductor wire and grounded brushes; in contrast, mirrors are insulated, so this type of electrocution event is unlikely to occur. However, our trial included fewer groups and poles for both brushes and mirrors than the other treatments.

The number of active small mammal holes counted in the year prior to the trial was associated with electrocution rates, probably because these were either a good proxy measure for small mammal abundance or because predatory birds used holes as an indicator of rodent abundance (Dixon et al. 2017). Large birds of prey can use power poles as hunting perches, and might be expected to perch more frequently at poles in localities with, or indications of, greater prey abundance (Prather and Messmer 2010).

Insulation covers for insulators and the adjacent section of conductor cable have been widely adopted internationally as a mitigation measure to reduce avian electrocution rates, as have perch management techniques using deflectors and discouragers (APLIC 2006, Prinsen et al. 2012). Our assessment of different mitigation methods is applicable to other situations, but specific features of hardware design on poles, variation in the design of the mitigation materials, and different species of birds present in the vicinity of the line may influence the efficacy of the mitigation.

The cost of covering all 3 conductor wires of every line pole on this 56-km line would have been US$117,442, compared with US$12,184 for a combination of mounts and mirrors and US$84,513 for a combination of mounts and covers (see Supporting Information). The results of our trial indicate that these types of mitigation would reduce levels of electrocution. However, in addition to cost and initial efficacy, there are other factors that influence the merits of these different types of mitigation, particularly the long-term efficacy of the equipment and maintenance costs. Mounts represent a permanent fix, whereas covers are an additional unit requiring some level of maintenance because they can potentially break off (Guil et al. 2011). They may also result in damage to conductors from corona discharge and conductor abrasion, and cause problems such as flash-over or power creep as a result of dust or ice accumulation (Burnham et al. 2004, Göcsei et al. 2014). Likewise, mirrors will also have a maintenance cost; over a 5-year period, the primary cause of failure for rotating-mirror units on the Ullbayan–Munkhkhaan line was detachment from the cross-arm, most of which occurred in the first 2 years after deployment. Detachment failure may represent issues with the equipment itself, local environmental conditions (particularly wind), or quality of workmanship when deploying the units. Of those that did not become detached, survival was very good for ≥2 years after deployment with 94% still functioning, and 73% functioning after 5 years. The low cost of units and ability to safely replace detached and broken units without switching off the power means that renewal could potentially be conducted relatively inexpensively during routine line monitoring and maintenance. Though likely to be effective at reducing electrocution if placed at all 3 conductor phases, insulation covers are unlikely to be adopted at a widescale in Mongolia because of their high cost. Data on the efficacy of mitigation methods targeted at electrocution and collision can inform policy decisions and facilitate the process of developing national standards for power line mitigation in Mongolia (e.g., Dashnyam et al. 2016).

MANAGEMENT IMPLICATIONS

Electrocution is a major cause of raptor mortality in Mongolia that can be resolved with appropriate remediation. Current remediation efforts, where they are implemented by electricity distribution companies in Mongolia, rely primarily on fitting rotating mirror perch deterrents or various forms of perch deflectors such as spikes and brushes, which themselves may or may not be insulated. We have shown that uninsulated perch deflectors do not reduce electrocution rates, and we do not recommend their use as a form of mitigation management. While rotating mirrors perch deterrents did reduce electrocution rates, they were susceptible to breakdown and primarily target perch sites on the crossarms where they are fitted. Consequently, we do not recommend their use without ongoing replacement and maintenance, nor should they be used without an additional form of mitigation targeted at Phase 1 on the pole top.

Cover-up insulation on the live conductors reduced electrocution rates but the cost of imported equipment used in this trial is likely to be prohibitive for widescale adoption by Mongolian electricity distribution companies. Nonetheless, our study has shown the utility of the 'cover-up' principle of introducing an insulating barrier to prevent phase to ground electrocution events. Management options based on the cover-up principle can include insulation of the non-conduction components of the pole, such as the crossarm or concrete pole top, which can be less expensive and avoid potential issues arising from the insulation equipment having a detrimental effect on the conductors and disrupting power supplies.

ACKNOWLEDGMENTS

This trial was funded by and conducted on behalf of the Environment Agency-Abu Dhabi, with logistical support provided by the Sukhbaatar branch of the Eastern Energy System. We thank Ts. Purevsuren, G. Purev-Ochir and the local line surveyors J. Gombosuren and U. Boldbaatar. We thank the Associate Editor and reviewers for their valuable comments that greatly improved the manuscript.

LITERATURE CITED

Angelov, I., I. Hashim, and S. Oppel. 2013. Persistent electrocution mortality of Egyptian vultures *Neophron percnopterus* over 28 years in East Africa. Bird Conservation International 23:1–6.

Avery, M. L., and S. J. Werner. 2017. Frightening devices. Pages 159–174 *in* G. M. Linz, M. L. Avery, and R. A. Dolbeer, editors. Ecology and management of blackbirds (Icteridae) in North America. CRC Press, Boca Raton, Florida, USA.

Avian Power Line Interaction Committee [APLIC]. 2006. Suggested practices for avian protection on power lines: the state of the art in 2006. Edison Electric Institute, Washington, D.C., USA.

Barrientos, R., J. C. Alonso, C. Ponce, and C. Palacín. 2011. Meta-analysis of the effectiveness of marked wire in reducing avian collisions with power lines. Conservation Biology 25:893–903.

Bevanger, K. 1994. Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. Ibis 136:412–425.

Bishop, J., H. McKay, D. Parrott, and J. Allan. 2003. Review of international research literature regarding the effectiveness of auditory bird scaring techniques and potential alternatives. Central Science Laboratories for DEFRA, London, England, United Kingdom.

Burnham, J., R. Carlton, E. A. Cherney, G. Couret, K. T. Eldridge, M. Farzaneh, S. D. Frazier, R. S. Gorur, R. Harness, D. Shaffner, S. Siegel, and J. Varner. 2004. Preventive measures to reduce bird-related power outages—part I: electrocution and collision. IEEE Transactions on Power Delivery 19:1843–1847.

Chevallier, C., A. Hernández-Matías, J. Real, N. Vincent-Martin, A. Ravayrol, and A. Besnard. 2015. Retrofitting of power lines reduces mortality by electrocution in large birds: an example with the endangered Bonelli's eagle. Journal of Applied Ecology 52:1465–1473.

Dashnyam, B., Ts. Purevsuren, S. Amarsaikhan, D. Bataa, B. Buuveibaatar, and G. Dutson. 2016. Malfunction rates of bird flight diverters on powerlines in the Mongolian Gobi. Mongolian Journal of Biological Sciences 14:13–20.

del Hoyo, J., A. Elliott, J. Sargatal, D. A. Christie, and E. de Juana, editors. 2014. Handbook of the birds of the world alive. Lynx Edicions, Barcelona. <http://www.hbw.com/> Accessed 20 Jan 2018.

Dixon, A. 2010. The problem of raptor electrocution at electricity distribution lines. Falco 37:10–13.

Dixon, A. 2016. Commodification of the Saker falcon *Falco cherrug:* conservation problem or opportunity? Pages 69–89 *in* F. M. Angelici, editor. Problematic wildlife. Springer, Basel, Switzerland.

Dixon, A., B. Bold, P. Tsolmonjav, B. Galtbalt, and N. Batbayar. 2018. Efficacy of a mitigation method to reduce raptor electrocution at an electricity distribution line in Mongolia. Conservation Evidence 15:50–53.

Dixon, A., R. Maming, A. Gunga, G. Purev-Ochir, and N. Batbayar. 2013. The problem of raptor electrocution in Asia: case studies from Mongolia and China. Bird Conservation International 23:520–529.

Dixon, A., M. L. Rahman, B. Galtbalt, A. Gunga, B. Sugarsaikhan, and N. Batbayar. 2017. Avian electrocution rates associated with density of active small mammal holes and power-pole mitigation: implications for the conservation of Threatened raptors in Mongolia. Journal of Nature Conservation 36:14–19.

Dwyer, J. F., and K. Doloughan. 2014. Testing systems of avian perch deterrents on electric power distribution poles. Human–Wildlife Interactions 8:39–55.

Dwyer, J. F., R. E. Harness, and K. Donohue. 2014. Predictive model of avian electrocution risk on overhead power lines. Conservation Biology 28:159–168.

Dwyer, J. F., M. C. Tincher, R. E. Harness, and G. E. Kratz. 2016. Successful use of a perch deterrent to manipulate raptor perching on model power poles. Colorado Birds 50:166–174.

Ferrer, M. 2012. Birds and power lines: from conflict to solution. Endesa S. A. and Fundación Migres, Seville, Spain.

Ferrer, M., M. de La Riva, and J. Castroviejo. 1991. Electrocution of raptors on power lines in southwestern Spain. Journal of Field Ornithology 62:181–190.

Fox, N. C., and C. Wynn. 2010. The impact of electrocution on the New Zealand falcon (*Falco novaeseelandiae*). Notornis 57:71–74.

Göcsei, G., B. Németh, R. Cselkó, and I. Berta. 2014. Bird protection on medium voltage power lines—an experimental study on the Hungarian grid. Pages 460–464 *in* 2014 IEEE Electrical Insulation Conference, Philadelphia, Pennsylvania, USA.

Guil, F., M. Fernández-Olalla, R. Moreno-Opo, I. Mosqueda, M. E. Gómez, A. Aranda, A. Arredondo, J. Guzmán, J. Oria, L. M. González, and A. Margalida. 2011. Minimising mortality in endangered raptors due to power lines: the importance of spatial aggregation to optimize the application of mitigation measures. PLoS ONE 6(11):e28212.

Harness, R., S. Gombobaatar, and R. Yosef. 2008. Mongolian distribution power lines and raptor electrocutions. Rural Electric Power Conference, Charleston, South Carolina, USA.

Harness, R. E., P. R. Juvvadi, and J. F. Dwyer. 2013. Avian electrocutions in western Rajasthan, India. Journal of Raptor Research 47:352–364.

Hernández-Matías, A., J. Real, F. Parés, and R. Pradel. 2015. Electrocution threatens the viability of populations of the endangered Bonelli's eagle (*Aquila fasciata*) in southern Europe. Biological Conservation 19:110–116.

Janss, G. F. E., and M. Ferrer. 1999. Mitigation of raptor electrocution on steel power poles. Wildlife Society Bulletin 27:263–273.

Jenkins, A. R., J. Smallie, and M. Diamond. 2010. Avian collisions with power lines: a global review of causes and mitigation, with a South African perspective. Bird Conservation International 20:263–278.

Kemper, C. M., G. S. Court, and J. A. Beck. 2013. Estimating raptor electrocution mortality on distribution power lines in Alberta, Canada. Journal of Wildlife Management 77:1342–1352.

Ledger, J. A., and H. J. Annegarn. 1981. Electrocution hazards to the cape vulture *Gyps coprotheres* in South Africa. Biological Conservation 20:15–24.

Lehman, R. N., P. L. Kennedy, and J. A. Savidge. 2007. The state of the art in raptor electrocution research: a global review. Biological Conservation 136:159–174.

Lehman, R. N., J. A. Savidge, P. L. Kennedy, and R. E. Harness. 2010. Raptor electrocution rates for a utility in the intermountain western United States. Journal of Wildlife Management 74:459–470.

Muggeo, V. 2008. Segmented: an R package to fit regression models with broken-line relationship. Rnews 81:20–25.

Negro, J. J., and M. Ferrer. 1995. Mitigating measures to reduce electrocution of birds on power lines: a comment on Bevanger's review. Ibis 137:423–424.

Prather, P. R., and T. A. Messmer. 2010. Raptor and corvid response to power distribution line perch deterrents in Utah. Journal of Wildlife Management 74:796–800.

Prinsen, H. A. M., G. C. Boere, N. Píres, and J. J. Smallie. 2011. Review of the conflict between migratory birds and electricity power grids in the African–Eurasian region. CMS/AEWA Technical Series No. 42, Bonn, Germany.

Prinsen, H. A. M., J. J. Smallie, G. C. Boere, and N. Píres. 2012. Guidelines on how to avoid or mitigate impact of electricity power grids on migratory birds in the African–Eurasian Region. AEWA Conservation Guidelines No. 14, CMS Technical Series No. 29, AEWA Technical Series No. 50, CMS Raptors MOU Technical Series No. 3, Bonn, Germany.

Purevdorj, A., and G. Sundev. 2012. The assessment of high risk utility lines and conservation of globally threatened pole nesting steppe raptors in Mongolia. Ornis Mongolica 1:2–12.

R Development Core Team. 2013. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Tintó, A., J. Real, and S. Mañosa. 2010. Predicting and correcting electrocution of birds in Mediterranean areas. Journal of Wildlife Management 74:1852–1862.

Associate Editor: Boal.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article. Relative cost of the mitigation materials used the trial.

Summary for Online TOC: We examined the efficacy of different mitigation methods aimed at reducing raptor electrocution rates at a power distribution poles in Mongolia. Cover-up insulation on live conductors, reconfiguration of pin-insulator mounts at the top of the pole and rotating mirror perch deterrents all reduced electrocution rates, whereas metal brush perch deflectors on the crossarm did not.