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Review

AVIAN ELECTROCUTIONS ON POWER LINES IN KAZAKHSTAN AND RUSSIA

ELECTROCUCIONES DE AVES EN TENDIDOS ELÉCTRICOS EN KAZAJISTÁN Y RUSIA

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SUMMARY.—Electrocutions involving power lines negatively impact avian populations on six continents. Affected species and mitigation strategies to minimise these effects are well described in parts of North America, Europe and southern Africa and are being developed in Asia, Australia and South America. Probably the most geographically dispersed electric system in the world is in Russia, where avian electrocutions have been documented since the 1970s. Research into avian electrocutions in Kazakhstan and southern Russia is extensive but is largely unknown outside Russia, which limits opportunities to consider cumulative regional effects. This review summarises what is known of avian electrocutions in Kazakhstan and Russia. Avian electrocutions on power lines were first identified in Russia in 1937, with concerns focused on impacts on electric system reliability, not wildlife populations. Electrocutions increased substantially in the 1970s when construction standards transitioned from wooden poles with wooden crossarms, which posed relatively low risk, to concrete pylons with steel crossarms, which posed and continue to pose much higher risks. Impacts to raptor populations are greatest where 6-10kV electric systems traverse vast arid landscapes with few natural tall perches. Birds perching on pylons can simultaneously contact live (energised) conductors and earthed (grounded) crossarms, creating an electrical circuit. Raptors are the bird group most often electrocuted, and this source of non-natural mortality is contributing to declines in Asian raptor populations. For example, Steppe Eagle *Aquila nipalensis* populations have collapsed in the Caspian steppes of Kazakhstan and southern Russia, declining from 20,000 pairs to 1,100 pairs. Fines for electrocutions codified in Russian law are intended to persuade Russian electric utilities to implement mitigation measures, but because fines are rarely enforced either within Russia or within neighbouring countries, mitigation measures are largely omitted even in new construction, and even in places with extensive documentation of electrocutions. Importantly, electric systems are similar across the many countries of the former Soviet Union that now share international boundaries and connected electric systems, probably

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posing substantial cumulative risks for migrant birds traversing the region.—Dwyer, J.F., Karyakin, I.V., Garrido López, J.R. & Nikolenko, E.G. (2023). Avian electrocutions on power lines in Kazakhstan and Russia. *Ardeola*, 70: 3-27.

Key words: *Aquila nipalensis,* corvid, electrocution, falcon, kestrel, mitigation, retrofitting.

RESUMEN.—Las electrocuciones en tendidos eléctricos afectan negativamente a las poblaciones de aves en los seis continentes. Las especies afectadas y las estrategias de mitigación para minimizar estos efectos están bien descritas en Norteamérica, Europa y el sur de África, y se están desarrollando en Asia, Australia y Sudamérica. Probablemente, la red eléctrica más dispersa geográficamente en el mundo se encuentra en Rusia, el país más grande del planeta, donde se han documentado electrocuciones de aves desde la década de 1970. La investigación sobre las electrocuciones de aves en Kazajistán y Rusia es extensa, pero se desconoce en gran medida fuera de Rusia, lo que limita las oportunidades de tener en cuenta los efectos regionales acumulativos. Esta revisión resume la información existente sobre las electrocuciones de aves en Kazajistán y Rusia. Las electrocuciones de aves en las líneas eléctricas se identificaron por primera vez en Rusia en 1937, ocasionando preocupación sobre el impacto en el funcionamiento de la red eléctrica, no sobre su impacto sobre las poblaciones de fauna. Los impactos aumentaron sustancialmente en la década de 1970, cuando se dejaron de utilizar apoyos con crucetas y postes de madera, con un riesgo relativamente bajo, pasando a utilizar apoyos de hormigón con crucetas de acero, que suponían, y siguen suponiendo, un riesgo mucho mayor. Los impactos sobre las poblaciones de aves rapaces son mayores donde los sistemas eléctricos de 6-10 kV atraviesan vastos paisajes áridos con pocos posaderos naturales. Las aves que se posan en los postes pueden entrar en contacto simultáneamente con conductores energizados y crucetas conectadas a tierra, creando un circuito eléctrico. Las rapaces se electrocutan con mayor frecuencia y sus electrocuciones están contribuyendo a la disminución de las poblaciones de rapaces asiáticas. Por ejemplo, las poblaciones de águila de estepa *Aquila nipalensis* se han desplomado en las estepas del Caspio en Kazajistán, Rusia y Ucrania, pasando de 20.000 parejas a 1.100. Las sanciones por electrocución tipificadas en la legislación rusa pretenden persuadir a las empresas eléctricas para que apliquen medidas de mitigación, pero como rara vez se aplican ni en Rusia ni en los países vecinos, las medidas de mitigación rara vez se llevan a cabo, incluso en las nuevas construcciones y en lugares con una amplia documentación de muertes por electrocución. Es importante destacar que los sistemas eléctricos son similares en los numerosos países de la antigua Unión Soviética que ahora comparten fronteras internacionales y sistemas eléctricos conectados, lo que muy probablemente plantea riesgos acumulativos sustanciales para las aves migratorias que atraviesan la región.—Dwyer, J.F., Karyakin, I.V., Garrido López, J.R. y Nikolenko, E.G. (2023). Electrocuciones de aves en tendidos eléctricos en Kazajistán y Rusia. *Ardeola*, 70: 3-27.

Palabras clave: adaptación, *Aquila nipalensis,* cernícalo, córvidos, electrocución, halcón, mitigación.

INTRODUCTION

Since the end of the 19th century, human populations worldwide have increasingly relied on electric power. Provision of electricity is most often accomplished by transmitting and distributing power through wires suspended from wooden poles, concrete pylons and steel towers. This approach minimises various costs associated with constructing and maintaining power lines. The approach also creates novel perching and nesting locations for birds.

Some birds can benefit from elevated power lines (Karyakin, 2008a; Tryjanowski *et al*., 2014; Ferrer *et al.,* 2020), for example, using them as perches from which to hunt, advertise territory, regulate body temperatures, roost or nest (Dwyer & Dalla Rosa, 2015; Kolnegari *et al*., 2020a; Moreira *et* *al*., 2018; Restani & Luck, 2020). Although power line infrastructure can create benefits for some species, on the whole, electrical infrastructure is probably more harmful to avian populations than beneficial due to electrocutions and collisions. In this review we focus on electrocution mortality in Kazakhstan and Southern Russia. Mortality attributable to power lines also occurs through collisions (Bernardino *et al*., 2018). However, because our source materials focused on electrocutions, this review does also.

Due to their large body sizes and their preference for elevated perches, raptors are particularly affected by electrocutions. For some species, electrocutions are either a contributing factor to, or the fundamental cause of, population decline (Slater *et al*., 2020). For example, in North America, electrocution is the primary cause of mortality for Golden Eagles *Aquila chrysaetos* (USFWS, 2016; Mojica *et al*., 2018), and also impacts numerous other raptor species and populations (Slater *et al*., 2020), including California Condors *Gymnogyps californianus*; (Rideout *et al*., 2012) and, in the Caribbean, Ridgway's Hawks *Buteo ridgwayi* (Dwyer *et al*., 2019b). In South America, Black-chested Buzzard-Eagles *Geranoaetus melanoleucus* and Chaco Eagles *Buteogallus coronatus* are affected (Orellana & Cornejo, 2010; Ibarra & De Lucca, 2015; Galmes *et al*., 2017). In Europe, Bonelli's Eagle *Aquila fasciata*, Eurasian Eagle-Owl *Bubo bubo* and Spanish Imperial Eagle *Aquila adalberti* were all once in decline due to electrocution mortality, although many populations have stabilised or increased in response to electrocution mitigation (Real *et al*., 2001; Fabrizio *et al*., 2004; Guil *et al*., 2015; Hernández-Matías *et al*., 2015). In Africa, Cape Vulture *Gyps coprotheres*, Egyptian Vulture *Neophron percnopterus*, Lappet-faced Vulture *Torgos tracheliotos*, Rüppell's Vulture *Gyps rueppelli*, White-backed Vulture *Gyps africanus* and White-headed Vulture *Trigonoceps occipitalis* are all affected (Smallie & Virani, 2010; Boshoff *et al*., 2011; Angelov *et al.,* 2013; Ogada *et al.,* 2016). Electrocution on power lines is also a primary threat to raptors in North Africa (Garrido *et al.,* 2021). In Australasia, and surrounding islands, New Zealand Falcon *Falco novaeseelandiae* and Tasmanian Wedge-tailed Eagle *Aquila audax fleayi* are affected (Bekessy *et al.,* 2009; Fox & Wynn, 2010). In Asia, electrocutions affect Saker Falcons *Falco cherrug* in Mongolia (Gombobaatar *et al.,* 2004), and numerous raptor populations throughout the Caspian steppe countries, including Kazakhstan and Russia.

Avian electrocution research is known primarily from work in North America and Europe (see citations in recent reviews by Bernardino *et al.,* 2018 and Slater *et al.,* 2020). Research from Asia is also increasing (e.g., Harness *et al.,* 2013; Dixon *et al.,* 2020; Kolnegari *et al.,* 2020a; Guil & Pérez-García, 2022). A great deal of research in Asia has been conducted in Kazakhstan and southern Russia, but that work is relatively inaccessible because it is published primarily in Russian, which is not widely spoken elsewhere. The journal *Pernatye khishchniki i ikh okhrana* (*Raptors Conservation*) has worked to address this through concurrently publishing articles in Russian and in English, but much work remains largely inaccessible, which limits the ability of the conservation community to learn from novel work conducted in the region. In this review, we summarise the history and data describing avian electrocutions in Kazakhstan and southern Russia, and we describe successes and setbacks in mitigating those events.

We conducted this review in three steps. First, we searched the Web of Science database for articles containing "power line" or "electrocution" + "Bird" or "Raptor" + "Russia" or "Kazakhstan". We reviewed all articles this search produced to find those relevant to our study. Second, we searched the archive of Raptors Conservation, the publication of the Russian Raptor Research and Conservation Network (RRRCN, 2022). Third, we referenced all materials in the personal libraries of each of the coauthors.

We also created a map to facilitate visualising the cumulative effects of electrocutions in the region we studied. To do so, we used information on electrocutions stored in an RRRCN database. We began by creating a grid with a cell size of 100 × 100km in Kazakhstan and 50 × 50km in Russia. Next, we populated each grid cell with values for landcover type, and where present, data describing the density of electrocuted birds found along power lines. Lastly, we used values for the density of electrocuted birds in each landcover type to populate cells that lacked electrocution density values. The data in the RRRCN database includes geospatial information from many but not all of the publications cited in this study, and includes unpublished data not yet used in any study. Because the map is based on partially unpublished data in the RRRCN database, involves assumptions across landcover types, and does not include data on power line locations, the map is useful for visualizing where electrocution potentials are low, medium, high, etc., but should not be interpreted as predictive in a statistical sense.

History of avian mortality on power lines (prior to 2000)

Avian mortality was first attributed to power lines in Russia in 1937 with a description of the widespread occurrence of electrocutions and suggested solutions (Formozov, 1981). At the time, birds were hunted for food and raptors in particular were persecuted as predators of domestic animals, so mitigation solutions were presented and implemented solely from the perspective of increasing the reliability of electric systems (Marfin, 1968). Conservation implications were not considered.

The impacts power lines had on wildlife in Kazakhstan and southern Russia were not considered until the 1970s when two key factors changed. First, the overhead electric system began to be changed from wooden power poles with wooden crossarms and generally low electrocution rates to concrete pylons with steel arms with much higher electrocution rates (Arais & Staltmanis, 1976, 1987). Second, attitudes towards wildlife generally, and raptors in particular, began to incorporate perceptions of aesthetic, cultural, intrinsic and utilitarian values (Galushin, 1980). As attitudes changed, researchers in Kazakhstan and Russia began to explore anthropogenic impacts on wildlife populations, including the effects of power lines on raptors.

In 1980, the first guidelines for preventing the electrocution of birds on power lines were published (Zvonov & Krivonosov, 1980). This publication drew the attention of Soviet zoologist journalist Vasily Peskov, who wrote "Birds on Wires" for the Komsomolskaya Pravda newspaper (Peskov, 1980). The article was influential to legislators who followed up in 1981 when the Union of Soviet Socialist Republics (USSR) Ministry of Energy order "On the development and implementation of measures to prevent the death of birds on overhead power lines" was passed (Ministry of Energy of the USSR, 1981). Avian electrocution studies also began to be conducted across the USSR at this time (Pererva & Blokhin, 1981; Zvonov & Krivonosov, 1981, 1984; Grazhdankin & Pererva, 1982). Early influential studies describing the impact of power lines on birds in Russia focused largely on Steppe Eagles *Aquila nipalensis* electrocuted on 6-10kV concrete pylons in the mostly treeless Astrakhan region of southern Russia between the Volga and Ural Rivers and the Caspian Sea (Figure 1; Shevchenko, 1978; Zvonov & Krivonosov, 1980; Peskov, 1980). These studies led to government-funded expeditions to the arid steppe, semi-desert and desert regions of the USSR, where large numbers of previously unknown electrocutions were discovered. (Pererva & Blokhin, 1981; Ministry of Energy of the USSR, 1981; Zvonov & Krivonosov, 1981). For example, Grazhdankin & Pererva (1982) found 496 electrocuted Steppe Eagles in 1980-1981 in the Caspian Sea region, and calculated mortality rates of 0.1 to 1.2 electrocuted Steppe Eagles/km of 6-10kV line.

In the 1990s, following the collapse of the USSR, and riding a wave of intensifying public interest in an environmental movement in Russia, two Federal laws "On Wildlife" (Russian Federation, 1995) and "On Environmental Protection" (Russian Federation,

FIG. 1.—Treeless landscapes of the Caspian steppe, including Kazakhstan and Russia, where large numbers of birds, particularly Steppe Eagles *Aquila nipalensis* and other raptors are electrocuted on power lines. Upper left: Grain fields in the forest-steppe of the Republic of Tatarstan (photo: Rinur Bekmansurov). Upper right: Pastures in the mountain forest-steppe of the Altai Republic (photo: Igor Karyakin). Bottom left: Pastures in the steppe of the Republic of Kalmykia (photo: Anton Abushin). Bottom right: Daurian steppe in the Trans-Baikal Territory (photo: Igor Karyakin).
[Paisajes desarbolados de la estepa del Caspio, incluyendo Kazajistán y Rusia, donde un gran número de aves, especialmente las águilas esteparias Aquila nipalensis *y otras rapaces, se electrocutan en los tendidos eléctricos. Arriba a la izquierda: Campos de cereal en la estepa leñosa de la República de Tataristán (foto: Rinur Bekmansurov). Arriba a la derecha: Pastos en la estepa leñosa de la República de Altái (foto: Igor Karyakin). Abajo a la izquierda: Pastos en la estepa de la República de Kalmukia (foto: Anton Abushin). Abajo a la derecha: Estepa de Daurian en la región de Trans-Baikal (foto: Igor Karyakin).]*

2002) were adopted by the Russian Federation. Both laws focused on wildlife conservation. In these laws, article 3 of 'On Environmental Protection' formed the basis of industrial environmental control carried out during economic and other activities, and Article 28 of On Wildlife specified that citizens and businesses must implement measures to prevent injuring or killing wildlife during private or commercial activities, including the production, transmission and distribution of electricity. Based on early findings relating types of power lines to rates of electrocutions "Requirements to prevent loss of wildlife during the implementation of production processes, and the operation of power lines, communication systems, highways, and pipelines" were developed in 1996. According to article 34 of this document power lines with a capacity of 6-35kV must be equipped with devices intended to minimise avian electrocution risks (Government of the Russian Federation, 1996). The Russian Ministry of Energy also explicitly prohibited the use of power transmission line supports with pin insulators within the habitats of large birds, specifically to try to reduce ongoing avian electrocutions (Ministry of Energy of the Russian Federation, 2003). According to Article 56 of On Wildlife, citizens and businesses who damaged wildlife or their habitats were required to compensate for the damage voluntarily, by court decision or by arbitration in accordance with the species-specific rates and methods defined for calculating damage to wildlife (Table 1).

The current avian electrocution crisis (2000 to present)

Unfortunately, the existence of a legal framework does not necessarily lead to effective law enforcement (Zamazkin, 2008). Despite the laws, in practice, power lines with high avian electrocution risks and rates continue to be built and operated widely, and fines usually go unassessed or unpaid.

From 2000 to the early 2020s, researchers have greatly expanded scientific understanding of the geographic and biological scope of avian electrocutions and collisions throughout the Caspian steppe countries, including Kazakhstan and southern Russia (Figure 2, Figure 3, Figure 4, Table S1, Table S2). This research has focused primarily on arid regions where trees are frequently scarce or absent, and pylons are the tallest objects in the landscape. Pylon height is important because in the absence of natural tall perches, pylons become particularly attractive perch locations for raptors and other birds. Our literature review revealed that reports of electrocution mortality greatly exceed those of collision mortality in Kazakhstan and southern Russia. Collision mortality also occurs (Karyakin *et al*., 2008; Barbazyuk & Petrischev, 2012), but is probably underestimated or unreported in our study area, as elsewhere in the world (Bernardino *et al*., 2018; Dwyer, 2020; Kettel *et al*., 2022). Raptors and corvids are the two avian groups most affected by electrocution mortality and almost always accounted for the highest numbers of electrocutions in the papers we reviewed (e.g., Barbazyuk, 2012; Karyakin, 2012; Satlykov, 2012a). Common species dominated lists of electrocuted birds, but species of conservation concern were also frequently reported.

One of the most affected species was the Steppe Eagle (Grazhdankin & Pererva, 1982) currently classified as endangered (BirdLife International, 2021). Steppe Eagle populations have collapsed in the Caspian Steppe region, declining from 20,000 pairs to 1,100 pairs (Karyakin, 2013). Carcass discovery data indicate electrocution as the primary cause of the decline (Karyakin & Novikova, 2006; Karyakin, 2012). For example, in just two studies, 80 Steppe Eagles were found electrocuted in 1979 and

TABLE 1

Fines assessable in Russia for each avian mortality attributed to anthropogenic causes including electrocution (Ministry of Natural Resources of Russia 2011, Ministry of Natural Resources of Russia 2012). In practice, fines are rarely enforced. * Estimates based on exchange rates on 1 January 2021 of ₽1 RUB = $0.0135 USD. The rate on 1 January 2022 was ₽1 RUB = $0.0134 indicating relative consistency over most of the time this manuscript was written.
*[Multas aplicables en Rusia por cada muerte de aves atribuida a causas humanas, incluida la electrocución (Ministry of Natural Resources of Russia 2011, Ministry of Natural Resources of Russia 2012). En la práctica, las multas rara vez se aplican. * Estimación basada en los tipos de conversión a 1 de enero de 2021 de ₽1 RUB = 0,0135 USD. El tipo de cambio a 1 de enero de 2022 era de ₽1 RUB = 0,0134 dólares, lo que indica una relativa consistencia durante la mayor parte del tiempo en que se escribió este manuscrito.]*

		Fine per Electrocution		
Common Name	**Scientific Name**	**Rubles**	**Dollar***	**Euro***
Saker Falcon, Peregrine Falcon	*Falco cherrug, F. peregrinus*	₽ 600,000	$ 8,160	€ 6,630,000
Golden Eagle	*Aquila chrysaetos*	₽ 300,000	$ 4,080	€ 3,315,000
Eastern Imperial Eagle	*Aquila heliaca*	₽ 100,000	$ 1,350	€ 1,105,000
White-Tailed Eagle	*Haliaeetus albicilla*	₽ 100,000	$ 1,350	€ 1,105,000
Cinereous Vulture	*Aegypius monachus*	₽ 100,000	$ 1,350	€ 1,105,000
Eagles to genus	*Aquila, Haliaeetus*	₽ 50,000	$ 675	€ 553,000
Steppe Eagle	*Aquila nipalensis*	₽ 50,000	$ 675	€ 553,000
Eurasian Eagle-Owl	*Bubo bubo*	₽ 50,000	$ 675	€ 276,000
Great Grey Shrike	*Lanius excubitor*	₽ 10,000	$ 135	€ 111,000
Crane species	*Gruiformes*	₽ 10,000	$ 135	€ 111,000
Stork and Heron species	*Ciconiiformes*	₽ 10,000	$ 135	€ 111,000
Hawks, Kites, Falcons	*Accipiter, Buteo, Milvus, Falco*	₽ 5,000	$ 68	€ 55,000
Owls	*Asio, Strix*	₽ 5,000	$ 68	€ 55,000
Great Spotted Woodpecker	*Dendrocopos major*	₽ 3,500	$ 47	€ 39,000
Eurasian Nightjar	*Caprimulgus europaeus*	₽ 2,000	$ 27	€ 22,000
Passerines	*Passeriformes, Corvidae*	₽ 1,000	$ 14	€ 11,000

103 in 1980 (Zvonov & Krivonosov, 1980; Zvonov & Krivonosov, 1981).

Other species frequently reported in electrocution studies in the arid region include the Eastern Imperial Eagle *Aquila heliaca* and Saker Falcon. Eastern Imperial Eagles are 'Vulnerable' (BirdLife International, 2019), and are frequently reported in electrocution studies in the region (Barbazyuk *et al*., 2010; Bekmansurov *et al*., 2012; Karyakin

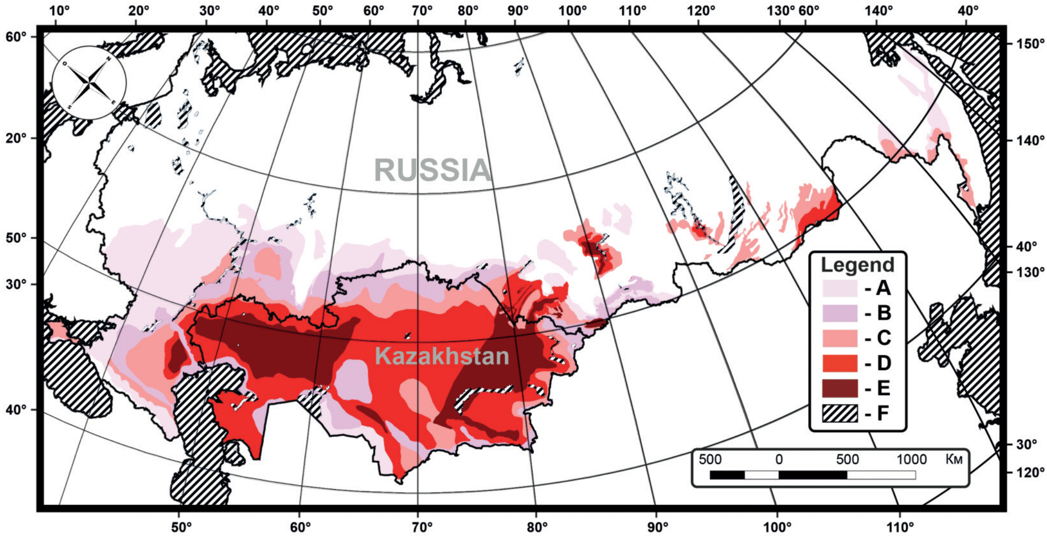

FIG. 2.—Raptor electrocution rates on 6-10kV power lines in the Caspian steppe, Kazakhstan, and Russia. A) Low mortality rates involving 1-2 species annually and <0.5 raptors/10km of power lines. B) Moderate mortality rates involving 3-5 species annually and 0.5-0.9 raptors/10km of power lines. C) High mortality rates involving 3-5 species and 1.0-2.9 raptors/10km of power lines. D) Very high mortality rates involving 3-5 species and 3.0-4.9 raptors/10km of power lines. E) Extreme mortality rates involving 3-5 species and ≥ 5.0 raptors/10km of power lines. F) Large water bodies (from: Karyakin, 2016).
[Tasas de electrocución de rapaces en líneas eléctricas de 6-10 kV en la estepa del Caspio, Kazajistán y Rusia. A) Tasas de mortalidad bajas que afectan a 1-2 especies anualmente y < 0,5 rapaces/10 km de líneas eléctricas. B) Tasas de mortalidad moderadas que afectan a 3-5 especies anualmente y 0,5-0,9 rapaces/10 km de líneas eléctricas. C) Tasas de mortalidad elevadas que afectan a 3-5 especies y 1,0-2,9 rapaces/10 km de líneas eléctricas. D) Tasas de mortalidad muy elevadas que afectan a 3-5 especies y a 3,0-4,9 rapaces/10 km de líneas eléctricas. E) Tasas de mortalidad extremas que afectan a 3-5 especies y ≥ 5,0 rapaces/10 km de líneas eléctricas. F) Grandes masas de agua (extraído de Karyakin, 2016).]

& Vagin, 2015), and in eastern Europe (Lazarova *et al*., 2020; Demerdzhiev *et al.,* 2015; Gális *et al*., 2019). 'Endangered' Saker Falcons (BirdLife International, 2022) have also been identified in field studies of electrocution in Russia (Karyakin, 2012), and are widely reported in the electrocution literature throughout their range (e.g., Demeter *et al.,* 2018; Gális *et al.,* 2019; Dixon *et al.,* 2020). Numerous other raptor species included in the Red Data Book of Russia (Pavlov *et al*., 2021), due to their special conservation status within the country, are also included in reports of avian electrocution in Kazakhstan and southern Russia. For example, they include Golden Eagles and Lesser Kestrels *Falco naumanni* (Gadzhiev & Melnikov, 2012; Gadzhiev, 2013; Goroshko, 2017).

Cumulatively, the studies included in this review document over 11,000 avian mortalities attributed primarily to electrocution, with a total of 266 of Russia's 789 bird species identified as mortalities in electrocution studies (Saltykov, 2016). Some researchers conservatively estimated that nine to ten times as many birds were electrocuted in their respective study areas than were found (Matsyna & Zimazkin, 2010; Karyakin *et*

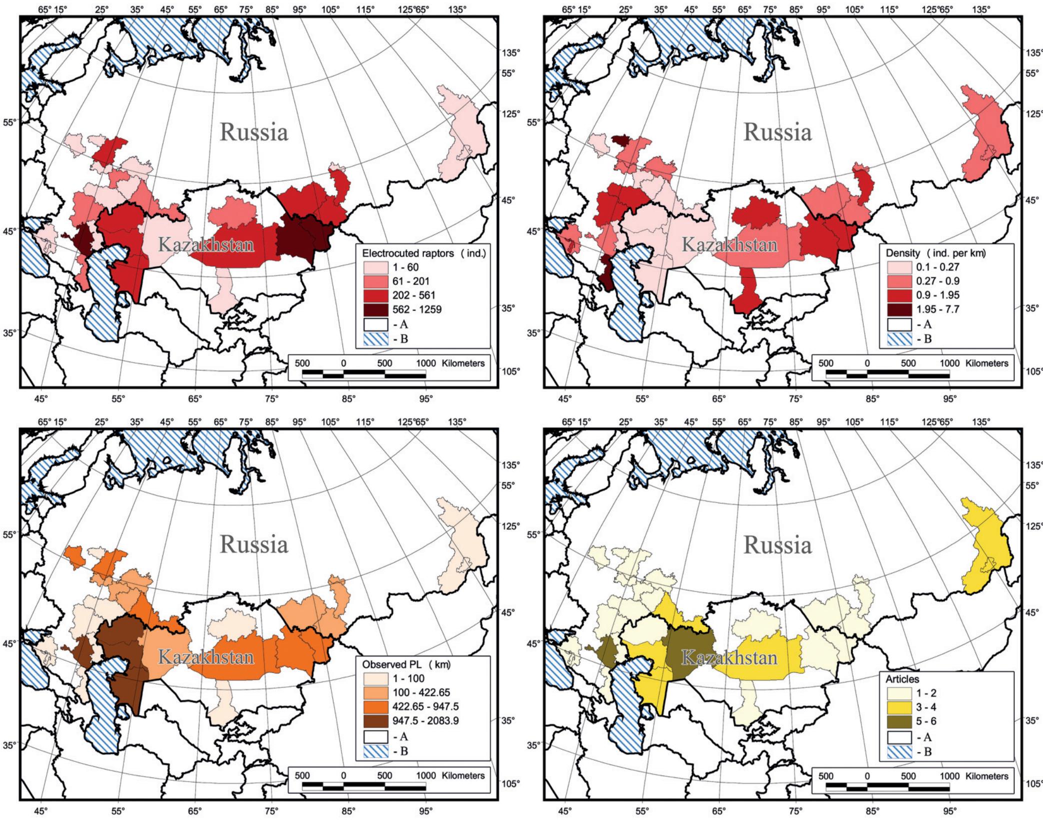

FIG. 3.—Summary data for avian electrocutions in Kazakhstan and southern Russia, according to publications in Table S1 and Table S2. Top left: Regions ranked by number of birds of prey electrocuted. Top right: Regions ranked by the density of electrocutions of birds of prey. Bottom left: Regions ranked by the length of surveyed power lines (PL). Bottom right: Regions ranked by the number of publications on avian electrocutions.

[Resumen de datos de electrocuciones en aves en Kazajistán y el sur de Rusia según las publicaciones citadas en la Tabla S1 y la Tabla S2. Arriba a la izquierda: Regiones clasificadas según el número de aves rapaces electrocutadas. Arriba a la derecha: Regiones clasificadas según la densidad de aves rapaces electrocutadas. Abajo a la izquierda: Regiones clasificadas según la longitud de las líneas eléctricas estudiadas (PL). Abajo a la derecha: Regiones clasificadas según el número de publicaciones sobre electrocuciones de aves.]

al., 2013a). Other researchers suggested 34 to 36 times as many birds were electrocuted as were found (Matsyna *et al.,* 2011a; Nikolenko, 2011); and the highest estimates suggested 90 times (Karyakin *et al*., 2009) to 246 times (Saltykov, 1999) as many birds were electrocuted annually in the study area as were found during surveys. Even if the highest estimates are too high, and moderate estimates in the 35× range are used for inference, totalling the numbers reported across studies indicates that hundreds of thousands of avian electrocution mortalities are occurring annually on the power lines studied in Kazakhstan and southern Russia. It is important to note that most power lines

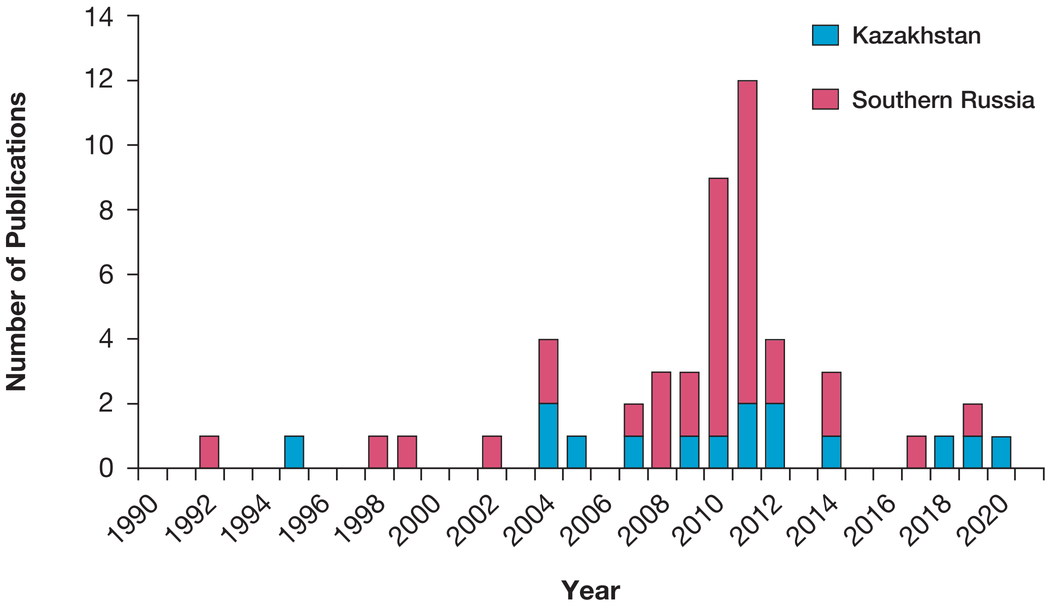

FIG. 4.—Publication dates of articles included in Table S1 and Table S2, Studies of Avian Electrocution in Kazakhstan and southern Russia.
[Fechas de publicación de los artículos incluidos en la Tabla S1 y Tabla S2, Estudios sobre electrocuciones de aves en Kazajistán y el sur de Rusia.]

are not included in electrocution studies, so even cumulative estimates need extrapolation to begin to indicate the true numbers of affected birds.

Electrocutions are most frequently reported on concrete pylons with steel arms supporting 6-10kV electric systems. These configurations place uninsulated live wires as close as a few centimetres from earthed elements (Arais & Staltmanis, 1976, 1987). They are also widespread throughout the region. Electrocutions are especially common when these types of structure include multiple pylons supporting pylon-mounted equipment (Shnayder *et al*., 2020). This configuration creates more instances of conductors near earthed supports on a single structure, and also frequently includes live jumper wires connecting conductors to one another and to live equipment, further increasing avian electrocution risks.

ELECTROCUTION MITIGATION MEASURES

Avian electrocution mitigation in Russia focused initially on incorporating perch deterrents and supplementary perches into pylon designs. Two widespread early mitigation measures were the "moustache" crossarm and the installation of an extra insulator near each conductor (Figure 5; Zvonov & Krivonosov, 1981; Grazhdankin & Pererva, 1982; "Glavniiproekt Selenergoproekt", 1985). These configurations were intended to limit birds perching adjacent to conductors, but neither approach was effective. Instead, both increased the frequency of avian electrocutions (General Directorate of Science and Technology, 1989; Karyakin & Barabashin, 2005; Matsyna *et al*., 2012), leading to the conclusion that these approaches should be discontinued (General Directorate of Science and Technology, 1989). This failure of the

FIG. 5.—Pylon modifications were ineffective in preventing birds from perching on 6-10kV power lines in Kazakhstan and Russia. Top left: The glass portion of extra insulators installed near each phase has fallen off, leaving the earthed, conductive centre post exposed (photo: Aleksander Matsina). Top right: The wooden crossbar installed with a supplementary perch has fallen off, leaving the earthed, conductive crossbar exposed (photo: Aleksander Matsina). Centre left: Steppe Eagles *Aquila nipalensis* perched on a pylon with a "moustache" arm intended to prevent perching near conductors (photo: Ilya Smelansky). Centre right: Eastern Imperial Eagle *Aquila heliaca* on a supplementary perch (photo: Anna Barashkova). Bottom Left: Steppe Eagles perched on a pylon with 35kV suspended insulators. Bottom right: Eastern Imperial Eagle perched on the unprotected upper insulator of a 10kV power pole (photo: Elena Shnayder). *[Las modificaciones de los apoyos no fueron estrategias eficaces para evitar que las aves se posaran en las líneas eléctricas de 6-10 kV en Kazajistán y Rusia. Arriba a la izquierda: La parte de vidrio de los aisladores adicionales instalados cerca de cada fase se ha caído, dejando al descubierto el conductor central conectado a tierra (foto: Aleksander Matsina). Arriba a la derecha: El travesaño de madera instalado con un posadero adicional se ha caído, dejando al descubierto el travesaño conductor conectado a tierra (foto: Aleksander Matsina). Centro izquierda: Águilas esteparias* Aquila nipalensis *posadas en un apoyo con un posadero tipo "bigote" destinado a evitar que se posen cerca de los conductores (foto: Ilya Smelansky). Centro derecha: Águila imperial oriental* Aquila heliaca *en un posadero adicional (foto: Anna Barashkova). Abajo a la izquierda: Águilas esteparias posadas en un apoyo con aisladores suspendidos de 35 kV. Abajo a la derecha: Águila imperial oriental posada en el aislador superior desprotegido de un poste eléctrico de 10 kV (foto: Elena Shnayder).]*

"Soviet bird protection science", combined with the collapse of the USSR, delayed progress in bird electrocution mitigation in the region for many years. Thereafter, mitigation strategies shifted to improvising insulator covers through installation of tyres and plastic bottles over insulators. These approaches were at least partially effective in the short-term but they were not likely to remain on pylons long-term, and they were not regulated or approved by the Ministry of Energy (Medzhidov *et al*., 2005). Consequently, these approaches were also discontinued and either dismantled or allowed to degrade in place.

Although early mitigation designs and strategies were unsuccessful, they increased awareness and led to two important developments. First, the Russian Bird Conservation Union (Saltykov, 2012a) and two non-governmental organisations, the "Dront" Ecological Centre (Birds and Power Lines, 2015a) and the Siberian Environmental Centre (Birds and Power Lines, 2015b), expanded work to include concerns related to avian electrocution. Second, development began of commercial Russian-made Bird Protection Devices (BPDs) designed specifically to fit the 6-10kV pylons (Figure 6) used throughout Kazakhstan, Russia and other former members of the USSR (Saltykov, 2003a). The BPDs were designed to meet international standards for product retention and effectiveness (Matsyna, 2008; Tetnev, 2012). Their availability and effectiveness has been crucial to the widespread deployment of avian protection measures, facilitating coordinated efforts to mitigate avian electrocutions across state and national boundaries.

Synergy created by conservation organisations in Russia and the availability of BPDs has facilitated distribution of information on avian electrocutions to electric utilities and National Parks throughout Kazakhstan and Russia, leading to widespread adoption of electrocution mitigation strategies. For example, since 2011 approximately 5,000 to 7,000km of power lines in Russia have been retrofitted with BPDs, reconfigured with suspended insulators, or rebuilt with insulated conductors. BPDs are now present in about 2/3 of Russia's regions to varying degrees, and coverage is expanding annually. Information on mitigating avian electrocutions was also included in the Red Data Books of seven subjects of the Russian Federation (approximately equivalent to states or provinces in other countries), and descriptions of retrofitting have been distributed to all nature reserves and national parks throughout Russia (Saltykov, 2018).

In 2012, the newly created Russian Raptor Research and Conservation Network, with the Birds and Power Lines Project (BPLP) (Birds and Power Lines, 2022) joined the above-mentioned NGOs. All these efforts have resulted in increased awareness of avian electrocutions leading to the adoption of requirements for preventing wildlife electrocutions in the Astrakhan, Moscow, Nizhny Novgorod and Volgograd regions, and in the Republic of Kalmykia. Increased awareness has also led the Russian Ministry of Natural Resources to include electrocution mitigation in legal mechanisms dedicated to the implementation of the Strategy for the Conservation of Rare and Threatened Species of Animals, Plants and Mushrooms (Ministry of Natural Resources of Russia, 2011, 2012, 2014). These developments expanded avian conservation efforts throughout Kazakhstan and Russia; far beyond the regions where most research on electrocutions has been conducted.

Eventually, by 2020, energy companies reconstructed or installed BPDs on dangerous power lines in Steppe Eagle and Saker Falcon habitat in the Altai-Sayan, Transbaikal Volga and Volga-Urals regions of Russia (Birds and Power Lines, 2022). The BPLP is also working with numerous Russian electric,

FIG. 6.—Bird Protection Devices (BPDs) designed specifically to fit the 6-10kV electric system in Kazakhstan and southern Russia. Top left: A plastic bottle used before BPDs were available in the region (photo: Adrey Saltykov from Medzhidov *et al.*, 2005). Top right: a Steppe Eagle *Aquila nipalensis* perched on insulated wire in Southern Ural, Russia (photo: Igor Karyakin). Centre right: A Eurasian Eagle-Owl *Bubo bubo* perched on a conductor cover in the Kalmykia, Russia (photo: Gennadiy Erdnenov). Bottom left: BPDs on conductors, jumpers, and equipment on a switch pylon (photo: EcoNIOKR). Bottom right: Steppe Eagle perched adjacent to a conductor fitted with a cover in Altai, Russia (photo: Márton Horváth).
[Dispositivos de protección de la avifauna (BPDs por sus siglas en inglés) diseñados específicamente para adaptarse al sistema eléctrico de 6-10 kV en Kazajistán y el sur de Rusia. Arriba a la izquierda: Una botella de plástico utilizada antes de que los BPD estuvieran disponibles en la región (foto: Adrey Saltykov de Medzhidov et al., 2005). Arriba a la derecha: águila esteparia Aquila nipalensis *posada en un cable aislado en el sur de los Urales, Rusia (foto: Igor Karyakin). Centro derecha: Búho real* Bubo bubo *posado en un protector de conductor en Kalmukia, Rusia (foto: Gennadiy Erdnenov). Abajo a la izquierda: BPDs sobre conductores, puentes y aparataje eléctrico en un apoyo con seccionador (foto: EcoNIOKR). Abajo a la derecha: Águila esteparia posada junto a un conductor protegido mediante una cubierta aislante en Altái, Rusia (foto: Márton Horváth).]*

cellular, and oil and gas companies to plan and implement reconstruction and retrofitting of numerous additional power lines, to reduce avian electrocutions throughout the region (Nikolenko & Karyakin, 2012). Through these efforts, mortality of focal species, including Eastern Imperial Eagle, Eurasian Eagle-Owl, Golden Eagle, Saker Falcon, Steppe Eagle and White-tailed Eagle *Haliaeetus albicilla* in the Altai-Sayan region and Transbaikalia has been reduced tenfold (Karyakin *et al*., 2013b; Goroshko, 2016, 2018).

In 2013, the World Wildlife Fund of Russia began partnering with the energy industry to minimise avian electrocutions, signing an agreement with the Federal Grid Company of Unified Energy System ("FGC UES") of Russia, focused on reducing the impacts of power lines on avian populations. One of the priority tasks defined by the agreement was to work in the Amur Basin of southern Siberia and southeast Russia to prevent electrocutions of Oriental Storks *Ciconia boyciana* nesting on pylons (Knizhnikov, 2016). Also in southern Siberia, the Altai-Sayan branch of the World Wildlife Fund of Russia has been working with the World Around You fund of Siberian Wellness since 2018 to prevent electrocutions of Steppe Eagles and Saker Falcons.

Another important mitigation measure undertaken in Russia has been increasing awareness by including avian electrocutions in the agendas of scientific conferences. Prior to 2015, when environmental non-governmental organisations were declared to be acting as foreign agents in Russia, the findings and resolutions of international conferences and large non-governmental organisations provided compelling arguments for managing power lines to reduce impacts on wildlife. For example, the Ulyanovsk Resolution "Birds and Power Lines – 2011" was adopted at the scientific-practical seminar "Problems of Bird Electrocution and Ornithological Safety on Medium Power Transmissions: Modern Scientific and Practical Experience" held in Ulyanovsk, Russia (Saltikov, 2011). In another example, the resolution "Eagles and Power Transmissions – 2013" was adopted as a result of the "Protection of Eagles from Death by Power Transmissions" round table at the "Palearctic Eagles: Study and Protection" International Scientific and Practical Conference held in Elabuga (Republic of Tatarstan, Russia; Saltikov, 2013). Conference resolutions such as these allowed researchers to convey their concerns to the environmental departments of energy companies, and to involve those organisations in solving avian electrocution concerns.

Comparison with other electric systems

The timing of the discovery of avian electrocutions in Russia was nearly concurrent with that of similar events elsewhere. For example, electrocutions were sporadically reported in Russia and in the United States in the early 1900s, but widespread observations did not begin to be recorded until the 1970s in Russia (Arais & Staltmanis, 1976, 1987), Europe and the United States (Olendorff, 1972; Boeker & Nickerson, 1975; Ferrer, 2012). The initiation of electrocution mitigation in Russia was also consistent with similar efforts elsewhere, with the first suggested solutions published in the 1980s in Russia (Formozov, 1981), and the 1970s in the United States (Miller *et al.,* 1975; Olendorff *et al*., 1981). In Europe, the Birds Directive (European Union, 1979) protected all birds in the European Union, without specifically mentioning power lines, forming the foundation for later laws regulating the construction of power lines to make them safe for birds (e.g., Andalusian Government, 1990).

In Russia, concrete pylons with steel arms in arid treeless landscapes are most frequently involved in electrocutions because the earthed configurations increase risk and because the lack of trees increases perching on pylons (Arais & Staltmanis, 1976, 1987; Matsyna *et al*., 2011a; Saltykov, 2012b; Karyakin, 2013). Similar patterns are also true elsewhere (Slater *et al*., 2020). For example, in countries as diverse as Hungary in Europe and the Dominican Republic in the Caribbean, concrete pylons with steel arms are associated with high electrocution rates, particularly in open landscapes or around nest sites (Demeter *et al*., 2018; Dwyer *et al*., 2019b; Horváth *et al*., 2010). In Spain, steel lattice distribution pylons with steel arms in open landscapes are associated with high rates of electrocution (Ferrer, 2012). There, installation of mitigation measures and construction of new power lines away from breeding areas has contributed to the recovery of the population of the globally 'Vulnerable' Spanish Imperial Eagle *Aquila adalberti* (López-López *et al*., 2011).

It is important to note that electric systems in Russia are similar to those in many other countries that were either part of the former USSR or that share international boundaries with former USSR countries, and thus share connected electric systems. For example, since the 1980s, electrocutions have caused significant mortality of protected birds in Hungary (Horváth *et al*., 2010). In those former USSR countries, lessons learned in Kazakhstan and Russia could be useful in anticipating pylons and habitats where electrocutions are likely, and in developing solutions.

We are unaware of relationships between avian electrocutions and power outages in Russia. However, these negative outcomes are well known from other electric systems. For example, in the United States, the Electric Power Research Institute reported that 9% and 2-10% (EPRI, 2001; EPRI, 2021 respectively) of avian electrocutions resulted in power outages, and Kemper *et al*. (2013), Dwyer & Mannan (2007) and the California Energy Commission (2005), reported corresponding figures of 6%, < 10% and 10-25% respectively. We did not find estimates for electrocutions resulting in power outages in our study area, but Kolnegari *et al*. (2020a) found 222 outages caused by incidents resulting from 235 avian electrocutions on electric power systems in Iran, which closely resemble those in Russia.

Avian electrocutions also cause wildfires. For example, Guil *et al*. (2017) determined that 2.4% of wildfires in Spain from 2000-2012 were caused by avian electrocutions. Dwyer *et al*. (2019a) identified wildfires resulting from avian electrocutions in Asia, Australia, Europe and North America, and Barnes *et al*. (2022) correlated bird-caused wildfires with fire-prone landscapes. Numerous authors (Guil *et al*., 2017; Dwyer *et al*., 2019a; Barnes *et al*., 2022) have suggested that retrofitting power lines to prevent avian electrocutions could reduce the occurrence of wildfires, a hypothesis supported by Fenster *et al*. (2021), who documented a statistically significant decline in wildfires attributable to avian electrocutions after retrofitting measures were implemented. Kolnegari *et al*. (2020a) found that in 2018, 3.6% of avian electrocutions resulted in wildfires in Iran. To date, relationships between avian electrocutions and wildfires have not been established in our study area, but this may be an important topic of future research.

Conclusions

Despite decades of research, the existence of a legal framework for conservation, and awareness of the likely relationships between avian electrocutions and disruptions to electric reliability, power lines throughout Kazakhstan and southern Russia continue to be constructed and operated with configurations that are deadly to birds. The resulting deaths are contributing to population-level effects on Steppe Eagles (Karyakin & Novikova, 2006; Karyakin, 2012; Karyakin, 2013) and Saker Falcons, which are endangered and declining across their range, due in part to electrocution (BirdLife International, 2022). Power line mortality is also impacting populations of the Peregrine Falcon *Falco peregrinus*, Common Kestrel *Falco tinnunculus*, Lesser Kestrel, Rough-legged Buzzard *Buteo lagopus*, Common Buzzard *Buteo buteo*, Golden Eagle, Eastern Imperial Eagle, White-tailed Eagle, Black Kite *Milvus migrans*, Eurasian Eagle-Owl, Hooded Crow *Corvus cornix*, and Eurasian Magpie *Pica pica* (Saltykov, 2003b; Barbazyuk *et al*., 2010; Matsyna *et al*., 2011a; Gadzhiev & Melnikov, 2012; Melnikov & Melnikova, 2012; Saltykov, 2012b; Gadzhiev, 2013; Karyakin *et al*., 2013b; Karyakin & Vagin, 2015; Pavlov & Senator, 2015).

Because many of the electrocuted birds are migrants and because many other power lines in the former USSR are built with similar configurations, the impact of avian electrocution in the region probably extends far beyond Kazakhstan and southern Russia. Specifically, the 6-10kV distribution electric system operating throughout Russia is constructed primarily of concrete pylons with steel crossarms. So too are the electric distribution systems of neighbouring China (Mei *et al*., 2008; Dixon *et al*., 2013), Mongolia (Gombobaatar *et al.,* 2004; Amartuvshin & Gombobaatar, 2012; Dixon *et al*., 2020), the Nakhchivan Autonomous Republic (Mammadov & Matsyura, 2020) and Ukraine (Andriushchenko & Popenko, 2012). Much of continental Asia, including India (Harness *et al*., 2013) and Iran (Kolnegari *et al*., 2020a, 2020b), has electric systems with similar constructions, as do some European countries formerly associated with the USSR, including Bulgaria (Demerdzhiev, 2014; Lazarova *et al*., 2020), Hungary (Demeter *et al*., 2018) and Slovakia (Gális *et al*., 2019), where very similar avian electrocution patterns exist.

Cooperation between energy companies, oil and gas companies, and large public organisations, including World Wildlife Fund-Russia, the RRRCN and the Russian Bird Conservation Union is helping to implement widespread and immediate conservation actions to stop the loss of avian biodiversity in Kazakhstan, Russia and numerous other countries in the region with similar power line configurations. These actions should focus on installing BPDs on existing power lines and on finding new power line designs that meet engineering needs while simultaneously reducing avian electrocution risks. Future research in Kazakhstan and southern Russia should also expand to distinguish electrocution mortality from collision mortality, to quantify the long-term effectiveness of mitigation measures and to study the effect of mortality reduction measures on affected populations in the region.

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Supplementary Electronic Material

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Table S1. Studies of avian electrocution in Russia.
[Estudios de electrocución de aves en Rusia.]

Table S2. Studies of avian electrocution in Russia.
[Estudios de electrocución de aves en Kazajistán.]

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