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Documenting and reducing avian electrocutions in Hungary: a conservation contribution from citizen scientists

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ABSTRACT—Electrocutions of birds on power structures is a global conservation concern that has not been thoroughly reported in all areas where it occurs. Here we provide information from citizen scientists describing 3,400 avian carcasses of at least 79 species found at the bases of 57,486 electrical pylons in Hungary. Of these carcasses, 3% were found at the bases of pylons retrofitted to reduce electrocution risk. On average, one carcass was found per 15 nonretrofitted pylons surveyed compared one carcass per 89 retrofitted pylons, an 83% difference in frequency. Electrocutions included 4 species of conservation concern in Hungary: Red-footed Falcons (*Falco vespertinus*), European Rollers (*Coracias garrulous*), Saker Falcons (*Falco cherrug*), and Eastern Imperial Eagles (*Aquila heliaca*). Only 3 of 104 (3%) electrocutions involving these species occurred on retrofitted pylons. Across birds of various sizes (small $\leq$25 cm long, medium 26–49 cm long, and large $\geq$50 cm long), differences in electrocution frequencies on nonretrofitted and retrofitted pylons were smallest for small birds, apparently because small birds could walk across the unprotected gaps in coverage directly below energized conductors. In this study, citizen scientists documented the breadth of the electrocution problem in Hungary but were not trained to record detailed pylon-specific configuration details. Rather, each pylon surveyed was categorized into one of 8 general configurations. Pylons with terminal connections were the most dangerous, accounting for 8% of pylons and 24% of electrocutions. Future mitigation may benefit from professional scientists conducting detailed analyses of how electrocutions occurred on retrofitted pylons. *Received 28 February 2017. Accepted 22 May 2017.*

Key words: corvid, eagle, electrocution, mortality, power line, pylon, raptor.

A madarakat érő áramütések dokumetálása és visszaszorítása Magyarországon önkéntesek közreműködésével

ABSTRACT (Hungarian)—A madarakat érő áramütés egy globális természetvédelmi probléma, amelynek dokumentálása azonban nem minden területen történik meg, ahol a probléma előfordul. Ebben a cikkben önkéntesek bevonásával gyűjtött információkat mutatunk be minimum 79 madárfaj 3,400 teteméről, amelyek összesen 57,486 elektromos oszlop környezetében kerültek elő. A tetemek 3%-a olyan oszlopoknál volt, amelyeken már történtek madárvédelmi technikai beavatkozások. Átlagosan 15 felmért átalakítás nélküli oszlopra jutott egy tetem, míg az átalakított oszlopok esetében minden 89 oszlopra jutott egy áldozat, ami 83%-os gyakoriságbeli eltérést jelent. Az áramütés négy olyan fajt is érint, amelyek a magyar természetvédelem számára kiemelt fontosságúak, úgymint: a kék vércse (*Falco vespertinus*), a szalakóta (*Coracias garrulus*), a kerecsensólyom (*Falco cherrug*) és a parlagi sas (*Aquila heliaca*). Az ezeket a fajokat érintő 104 áramütés közül csak 3 eset (3%) történt átalakított oszlopokon. A madarak méretét tekintve (kicsi $\leq$25 cm, közepes 26-49 cm és nagy $\geq$50 cm testhossz) az átalakított és átalakítás nélküli oszlopok között mutatkozó áramütés-gyakoriságbeli eltérés a kis testű madarak esetében volt a legkisebb, valószínűleg azért, mert a kis testű madarak át tudnak sétálni a burkolatlan elemek között és az áram alatt lévő vezetékek alatt. A felmérésekbe bevont önkéntesek dokumentálták a probléma magyarországi nagyságrendjét, de a vizsgált oszlopok konfigurációs sajátosságainak rögzítéséhez nem rendelkeztek megfelelő képzettséggel. Ehelyett minden egyes felmért oszlopot 8 oszlopkategóriába soroltak. A legveszélyesebbnek a feszítő elemekkel ellátott oszlopok bizonyultak, amelyek az összes oszlop 8%-át teszik ki, de az áramütések 24%-áért felelősek. A jövőbeli madárvédelmi beavatkozások számára hasznos lehet a már madárvédelmi szempontból átalakított oszlopokon tapasztalt áramütések tudományos módszerekkel történő részletes feltárása.

Kulcsszavak: áramütés, elektromos távvezetékek, mortalitás, oszlopok, ragadozó, sasok, varjúfélék.

Documentation of avian electrocutions on overhead electric infrastructure began almost immediately after construction of the world's first overhead electric power systems (Hallinan 1922, Lano 1927). Electrocutions were reported sporadically thereafter through the mid-20th century (Anderson 1933, Marshall 1940, Dilger 1954, Dickinson 1957) before becoming a prominent conservation concern in the 1970s (Olendorf 1972, Miller et al. 1975, Bijleveld and Goeldin 1976). As overhead electric systems spread, so too did avian electrocutions, and despite 40 years of research and mitigation efforts, electrocutions remain an international conservation concern (Bevanger 1998, Prinsen et al. 2011, Servicio Agrícola y Ganadero 2015). Electrocution is now often included in lists of anthropogenic impacts to declining raptor species. For example, Eagle Owls (*Bubo bubo*) in Italy (Sergio et al. 2004), Egyptian Vultures (*Neophron percnopterus*) in Egypt (Angelov et al. 2013), Golden Eagles (*Aquila chrysaetos*) in the United States (USFWS 2016),

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Spanish Booted Eagle (*Aquila pennata*) in Spain (Martinez et al. 2016), and Tasmanian Wedge-tailed Eagles (*Aquila audax fleayi*) in Australia (Bekessy et al. 2009) are all thought to be declining due in part to electrocution mortality.

Although concerns are global, avian electrocution research has been disseminated primarily from studies in Germany (Haas et al. 2005), South Africa (Van Rooyen et al. 2003, Boshoff et al. 2011, Jenkins et al. 2013), the Iberian Peninsula (Guil et al. 2011, López-López et al. 2011, Moreira et al. 2017), and the United States (Harness and Wilson 2001, Lehman et al. 2007, Dwyer et al. 2016). These centers of electrocution research contribute to overall perceptions of avian electrocution but do not reflect the global nature of the problem, either in terms of species affected or of the electrical configurations, materials, or local perceptions involved. Increasingly, research programs outside of these areas are facilitating broader understanding of avian electrocution. For example, the overhead electric systems of India and Mongolia are adjacent to, and engineered similarly to, the electrical systems of China, and each of these systems have been implicated in large numbers of avian electrocutions (Purevdorj and Sundev 2012, Dixon et al. 2013, Harness et al. 2013). Consolidated with studies documenting avian electrocutions in nearby Kazakhstan (Lasch et al. 2010), Russia (Karyakin et al. 2009, Barbazyuk et al. 2010), and Russian Siberia (Goroshko 2011), the potential exists for avian electrocution risk across much of Asia.

Avian electrocution may also be more prevalent across Europe than is currently recognized. For example, in addition to electrocutions in Germany (Haas et al. 2005), Italy (Rubolini et al. 2001), Portugal (de Sousa 2017, Moreira et al. 2017), and Spain (Ferrer 2012), >200 electrocutions of raptors, corvids, passerines, and other birds were documented in 6 Important Bird Areas in Bulgaria (Demerdzhiev et al. 2009, Gerdzhikov and Demerdzhiev 2009, Demerdzhiev 2014). Power line configurations in Bulgaria are similar to those in Croatia, Hungary, and Slovakia (MAVIR 2016), so concerns identified in Bulgaria may occur regionally. Avian electrocution in Hungary first became apparent in 1980 (Bagyura et al. 2004) and is either particularly problematic or particularly well documented, with an estimated 30,000–100,000 birds killed annually (Horváth et al. 2008, 2011; Tóth 2010). In 1991, Birdlife Hungary developed crossarm insulators designed to reduce electrocution risk, and from 1994 through 2002, >20,000 pylons were fitted with these insulators. This design was used as the sole solution to avian electrocution through the late 2000s when covers began to be installed on jumpers (the small wires linking terminal connections and energized equipment). Despite the high numbers of avian electrocutions in Hungary and the novel mitigation strategies used to address these incidents, data from Hungary have not been widely reported in English-language journals. This omission limits the ability of the scientific and conservation communities to learn from mitigation actions applied in Hungary or to consider potential regional effects of electrocution mortality in Hungary.

To address this communication gap, our primary objective was to document and report as many electrocuted birds of as many species as possible from Hungary. Our secondary objective was to compare mortality frequencies on pylons with and without retrofitting measures. In doing so, we compared null hypotheses that no differences in electrocution rates exist between nonretrofitted and retrofitted pylons, either overall or when considering specific pylon types or birds of different sizes. Some of the data included were previously released in local reports written in Hungarian (Horváth et al. 2010; Supplement S1), but here we offer a more extensive dataset than was previously released, provide new analyses of these data, and compare our findings to avian electrocutions reported elsewhere.

Methods

Study area

We conducted our study throughout Hungary (Fig. 1), an Eastern European country characterized by mixed habitats from forested mountains to open agricultural fields and grasslands. The Great Hungarian Plain east of Budapest is one of the most extensive floodplains of Europe, supporting numerous breeding, migratory, and wintering avian species. Because much of the area was grassland and open agricultural land or cropland, electric pylons were often the tallest structure on the landscape and consequently were attractive perches to many bird species.

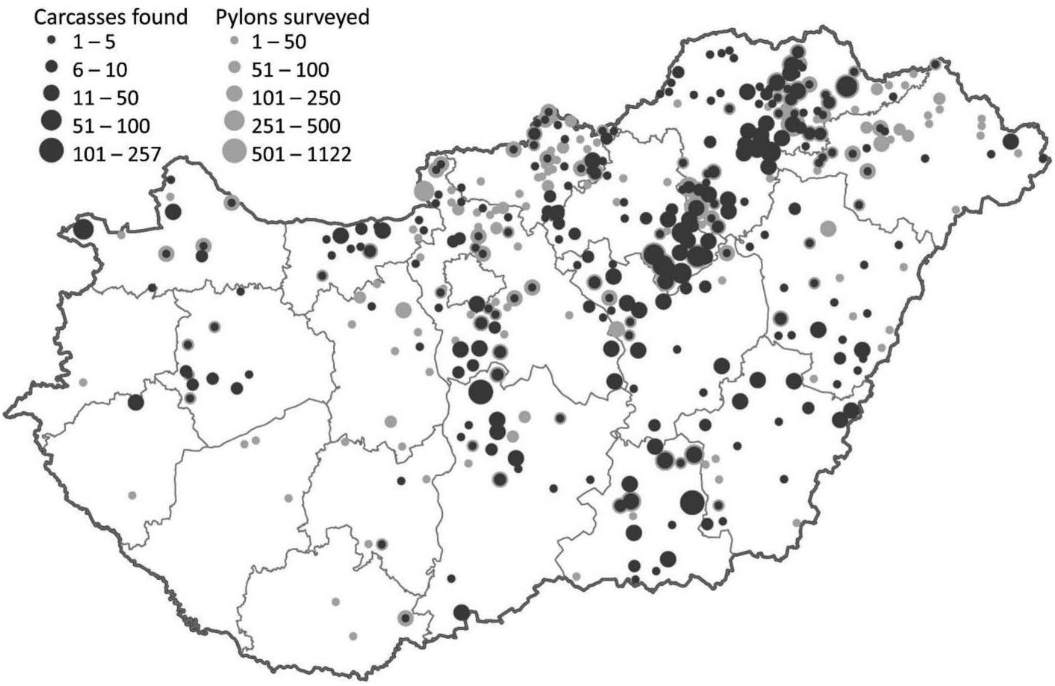

Figure 1. Locations of pylons surveyed and avian carcasses found in Hungary from 2004 to 2009. Reproduced from Horváth et al. (2010); Supplement S1.

Electric power is delivered within Hungary via one national transmission company, Hungarian Transmission System Operator Company Ltd. (MAVIR), and 5 regional 22 kV distribution service providers. These companies are responsible for ~700,000 pylons supporting 55,000 km of overhead electric lines (Horváth et al. 2010). Distribution pylons are constructed primarily of reinforced concrete vertical components and grounded metal arms. Roughly 560,000 of these pylons are in rural areas, where avian impacts have historically been associated primarily with electrocutions of raptors and corvids (Horváth et al. 2010).

Carcass survey protocol

We designed a survey protocol used by citizen scientist volunteers throughout Hungary from January 2004 through December 2014. In the context of avian research, citizen scientists are nonprofessional ornithologists, such as bird watchers, volunteer nest monitors, and bird banders (Cooper et al. 2015). Although nonprofessionals, citizen scientists often possess deep expertise drawn from years of personal engagement and study and can contribute important data to studies of avian ecology, facilitating access to broad-scale patterns not visible to individual researchers. For example, studies of raptor migration and raptor responses to climate change have relied on data from citizen scientists (Hussell and Inzunza 2008, Paprocki et al. 2017). To our knowledge, studies of raptor electrocution have not focused on citizen science, presumably because the technical aspects of overhead electrical systems were thought to preclude meaningful contributions by nonprofessionals.

In this study, we coordinated with citizen scientists to search for avian carcasses at the bases of pylons in Hungary because leveraging the availability of citizen scientists met our primary objective of documenting the greatest number and widest range of electrocutions possible. The approach allowed us to identify a broad distribution of electrocuted species and to compare broad categories of pylon types (described later). Citizen science data can be relatively coarse, however, sometimes precluding researcher's ability to rigorously measure all variables of potential interest (Ryder et al. 2010). In our study, use of citizen science data maximized detection of carcasses but limited our ability to identify pylon-specific attributes that might have contributed to a more detailed understanding of technical specifications associated with the electrocutions we report here. Consequently, in addressing our secondary objectives, our analyses are relatively coarse compared to studies such as Lehman et al. (2010) undertaken by professional scientists working in more compact study areas with expertise in both ornithology and overhead electric system.

Citizen scientists were instructed to search for the carcasses of electrocuted birds at the bases of a line of pylons of the citizen's choosing and to record the pylon configuration and any carcasses found for each pylon searched. Citizen scientists generally focused surveys in areas where they knew or suspected avian electrocutions might occur, especially where IUCN Red Listed threatened bird species were believed to be present. When surveys led to the detection of the electrocuted carcasses of species of special concern or the detection of large numbers of electrocuted birds of any species, citizen scientists sometimes repeated surveys of the same pylons within and across years. Thus, some areas known to be particularly dangerous were surveyed more frequently, which could be problematic if inferences were made between line segments or habitats, but in this study, inferences were made exclusively to pylon types. All pylon types surveyed were distributed throughout surveyed areas, seasons, and years and were surveyed without regard to configuration, eliminating potential bias resulting from citizen scientists preferentially surveying particular pylon types.

This nonrandom approach facilitated documentation of the scope of the electrocution problem in terms of species involved but simultaneously prevented us from reporting an estimate for total electrocution mortality in Hungary because sampled areas were not selected randomly. Despite the nonrandom approach, because citizen scientists surveyed continuous lines of pylons without regard to configuration and reported pylon configurations for all pylons surveyed, we were able to evaluate differences in electrocution rate by pylon configuration.

We defined 8 pylon configurations to which citizen scientists could assign surveyed pylons. All pylons were constructed with steel arms mounted on steel or steel-reinforced concrete vertical components. For each configuration, pylons were identified as nonretrofitted or retrofitted, creating 16 possible categories (Fig. 2–4). Nonretrofitted pylons included no retrofitting measures designed to mitigate avian electrocution risk; retrofitted pylons included covers on crossarms or jumpers (short wires connecting energized equipment) designed to reduce the possibility of simultaneous contact with energized wires and grounded structural components (Horváth et al. 2010). Pylons without jumpers were retrofitted by covering crossarms; pylons with jumpers were retrofitted by covering jumpers. Importantly, none of the pylons evaluated would have been considered fully retrofitted according to APLIC (2006) standards because in all cases, some phase-to-phase or phase-to-ground contact points persisted after retrofitting. Even minor errors in retrofitting can lead to electrocutions (Dwyer et al. 2017), so this study provides information on incomplete retrofitting, which has never before been specifically quantified in a scientific study.

In cases where pylons included aspects of multiple configurations, pylons were categorized based on the most complex configuration appropriate. For example, switches required wires to terminate on each side of a pylon so the utility could energize or de-energize discrete line sections. In these cases, the configuration was identified as a switch tower even though terminal connections were present. In other cases, where terminal connections existed without switches, the pylons were categorized according to terminal connections.

Each carcass found was identified to species when possible or to the most precise taxonomic category possible otherwise. We also estimated the body length of each species found based on previously published values (Mullarney et al. 1999). Information on body length is informative because avian electrocution is usually associated with large birds, particularly raptors, and retrofitting often specifically targets raptors (APLIC 2006, Lehman et al. 2010, Dwyer et al. 2015). Electrocution has been the primary cause of death in previous studies of avian carcasses found in association with pylons in Hungary (Bagyura et al.

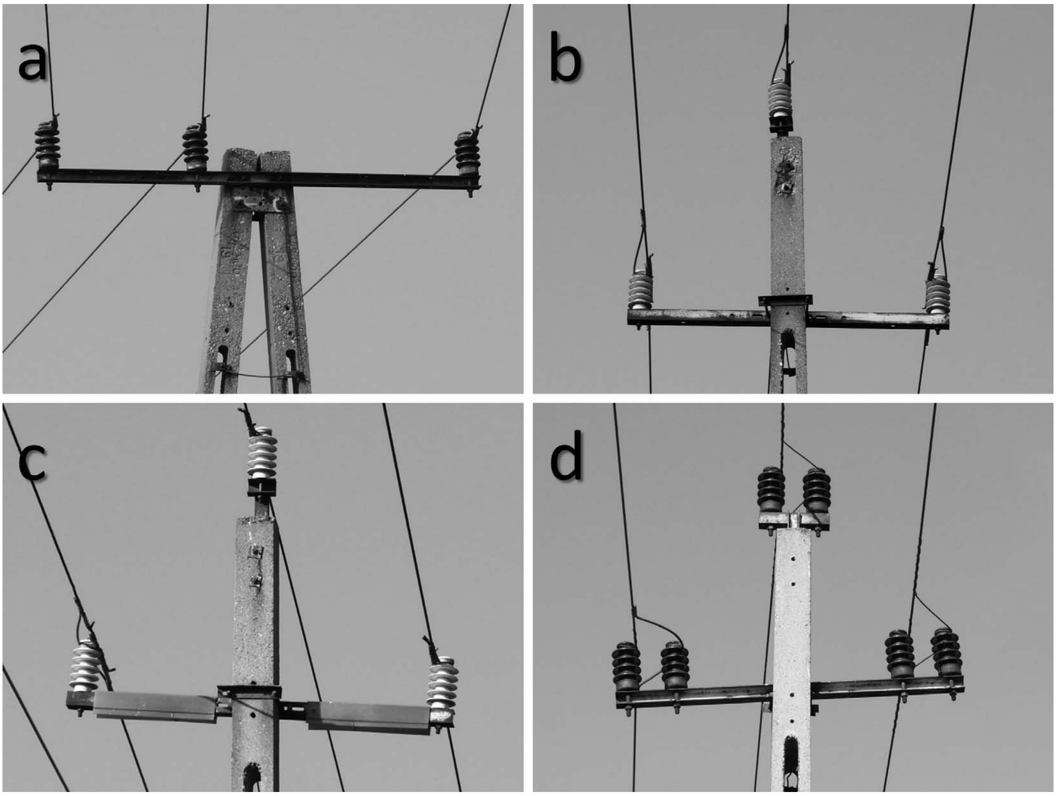

Figure 2. (a) Tangent, 1 insulator per Ø, 1 level; (b) tangent, 1 insulator per Ø, 2 level; (c) tangent, 1 insulator per Ø, 2 level, retrofitted with covers on the crossarm; (d) tangent, 2 insulators per Ø, 2 levels. Photo credit P. Tóth. Ø denotes phase.

2004, Tóth 2010, Fidlóczky et al. 2014). Consequently, we assumed electrocution to be the primary cause of death for carcasses reported in this study.

Statistical analyses

To evaluate differences in electrocution risk on nonretrofitted pylons compared to retrofitted pylons, our null hypothesis assumed electrocuted birds would be found below pylons in proportion to the frequency with which pylons occurred in surveys. For example, if 3.5% of pylons surveyed were switch towers without avian-friendly insulation, then 3.5% of carcasses should be attributable to pylons of this configuration. If carcasses were found in proportion to pylon configuration for all configurations, then we would not reject our null hypothesis. Our alternate hypothesis would be supported if any ratio of pylons to carcasses was not proportional (Dixon et al. 2013, Dwyer et al. 2013, Harness et al. 2013). We evaluated our hypothesis for all carcasses together and for small, medium, and large birds separately. To evaluate possible differences in retrofitting effects for birds of various sizes, we defined small birds as $\leq$25 cm long, medium-sized birds as 26–49 cm, and large birds as $\geq$50 cm. Only carcasses identified to species were included in this portion of our analyses.

We used 3 chi-square (χ^2) goodness of fit tests of independence to analyze our data. Because we conducted 3 tests of the same data, we implemented a Bonferroni correction to reduce the likelihood of Type I error, adjusting our critical level from $\alpha = 0.050$ to $\alpha = 0.017$. Thus, we considered *P* values of $\leq$0.017 statistically significant. In our first χ^2 test, we compared proportions of nonretrofitted and retrofitted pylons where carcasses were or were not found. This coarse analysis met recommendations for χ^2 tests but omitted information on pylon configurations. Our second χ^2 test distinguished 8 pylon configurations, each with 2 treatments (non-

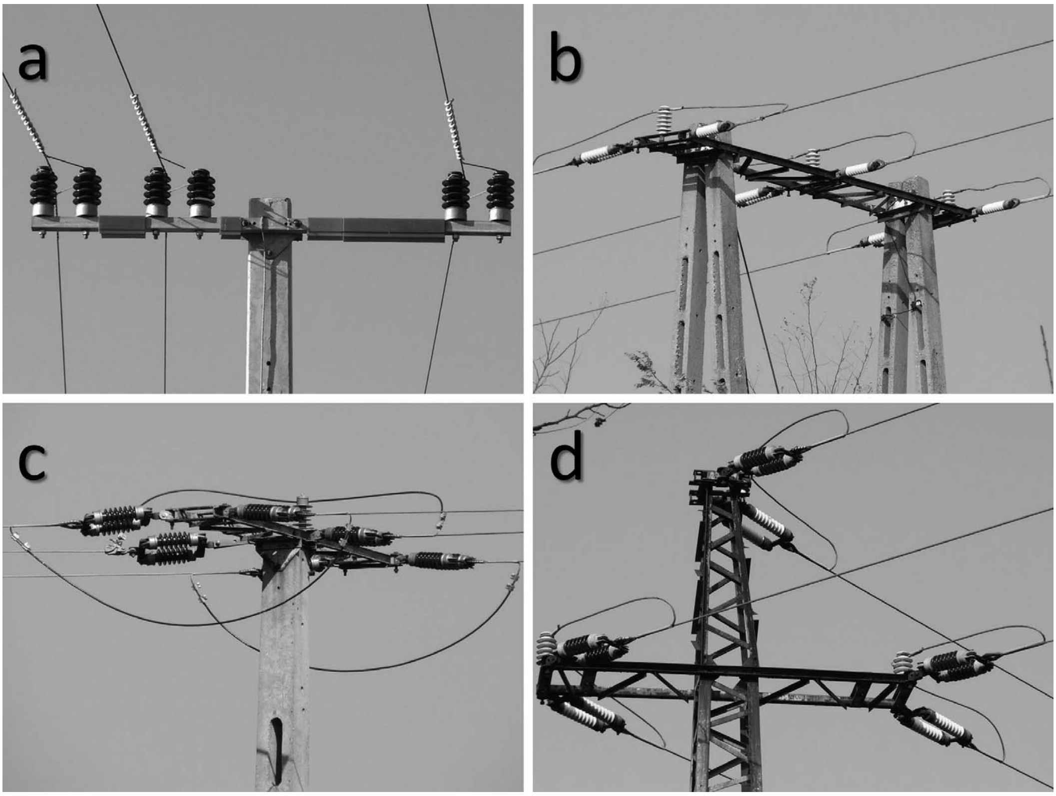

Figure 3. (a) Tangent, 2 insulators per Ø, 1 level, retrofitted with covers on the crossarm; (b) terminal connection, 1 level; (c) terminal connection, 1 level retrofitted with covers on jumpers; (d) terminal connection, 2 levels. Photo credit P. Tóth. Ø denotes phase.

retrofitted and retrofitted). This resulted in violations of recommended procedures for χ^2 testing because 4 observed values were <5. All of these values were for retrofitted pylons and were due to relatively few retrofitted pylons existing for some configurations, compounded by relatively few carcasses found at the bases of retrofitted pylons. Despite these violations, we proceeded with the χ^2 test because our first analysis provided support for overall conclusions regarding nonretrofitted and retrofitted pylons. This approach enables readers concerned with χ^2 best practices to choose to accept or disregard the second test. Our third test compared proportions of small, medium, and large electrocuted birds on nonretrofitted and retrofitted pylons.

Previous models of electrocution risk on wooden poles in the United States and concrete pylons in India (with configurations similar to pylons in Hungary) indicated that relative levels of risk could be quantified if numbers of conductors, numbers of jumpers, presence of grounding, and habitat were evaluated for each structure (pole or pylon) surveyed (Dwyer et al. 2013, Harness et al. 2013). Our dataset did not include these metrics because our citizen scientists were trained to record pylon tops into 1 of 16 categories, not to quantify pylon-top components. To facilitate comparison of our data to model results in other studies, we quantified typical numbers of energized and exposed conductors, jumpers, and terminal connections for each configuration. This simplified approach has been used successfully in other electrocution research where model results were intended to be accessible to nonprofessionals (Dwyer et al. 2013, Harness et al. 2013). We used these components to create a risk score for each configuration (Table 1), which omitted some of the nuance of more detailed models but facilitated general comparisons to other studies. It also made our results more accessible to conservationists who

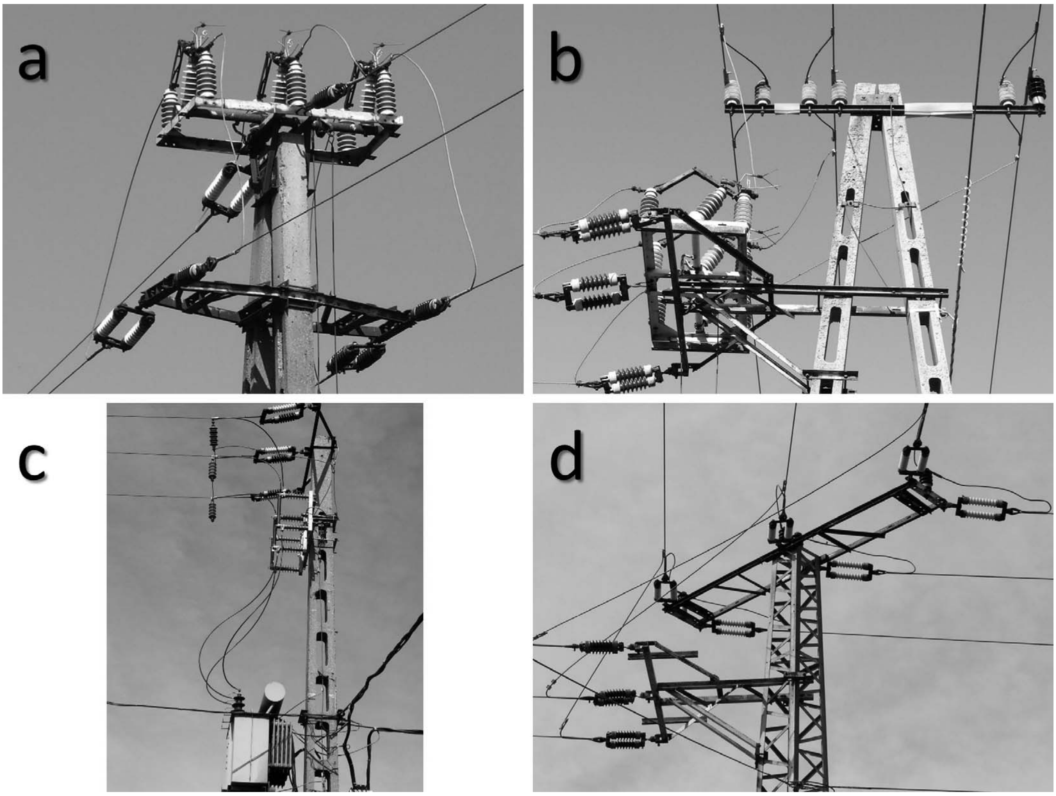

Figure 4. (a) Switch tower; (b) switch tower retrofitted with covers on the upper crossarm; (c) transformer pylon; (d) intersection pylon. Photo credit P. Tóth. Ø denotes phase.

may not have, or need, advanced technical understanding of pylon components. For analysis, we fitted a line between risk score and mean number of carcasses found per pylon configuration. We used the R^2 value for a best-fit line to identify the proportion of variation in carcasses per pylon explained by pylon configuration.

Results

From January 2004 through December 2014, citizen scientists surveyed 57,486 pylons, including 10,372 retrofitted pylons. Citizen scientists identified exactly 3,400 avian carcasses of at least 79 species (Supplement S1), including 4 species of conservation concern: Saker Falcon (*Falco cherrug*), Red-footed Falcon (*Falco vespertinus*), Eastern Imperial Eagle (*Aquila heliaca*), and European Roller (C*oracias garrulous*). Searchers found 117 carcasses of at least 17 species at the bases of retrofitted pylons (Supplement S2). Thus, 97% of carcasses were found under nonretrofitted pylons, even though these pylons made up only 82% of pylons surveyed, indicating an 83% difference from an average of one carcass found per 15 nonretrofitted pylons to one carcass found per 89 retrofitted pylons.

Some configurations were more dangerous than others when considering pooled nonretrofitted and retrofitted configurations ($\chi^2 = 459$, df $= 1$, $P < 0.001$; Table 2) or when comparing all 16 configuration*retrofitting categories ($\chi^2 = 3272$, df $= 15$, $P < 0.001$; Table 3). For example, nonretrofitted terminal connection 1-level and 2-level pylons were the most dangerous configurations (Fig. 5) given the differences between the proportion of the overhead electric system composed of these 2 configurations (8%) and the proportion of carcasses found dead at the bases of pylons with these configurations (24%). Overall, more carcasses (36%) were found under Tangent, 1 insulator per phase, 2-level pylons than any other configuration,

Table 1. Pylon configurations and risk scores assigned during surveys of overhead electric distribution systems in Hungary, January 2004 through December 2014. Ø denotes phase.

	Number of				
Pylon configuration	Overarm conductors	Jumpers	Terminal connections	Risk score	Figure
Tangent, 1 insulator per Ø, 1 level	3	0	0	3	1a
Tangent, 1 insulator per Ø, 1 level, retrofitted	0	0	0	0	[a]
Tangent, 1 insulator per Ø, 2 level	3	0	0	3	1b
Tangent, 1 insulator per Ø, 2 level, retrofitted	1	0	0	1	1c
Tangent, 2 insulators per Ø, 1 or 2 levels	3	3	0	6	1d
Tangent, 2 insulators per Ø, 1 or 2 levels, retrofitted	1	3	0	4	2a
Terminal connection, 1 level	0	3	6	9	2b
Terminal connection, 1 level, retrofitted	0	0	6	6	2c
Terminal connection, 2 levels	0	3	6	9	2d
Terminal connection, 2 levels, retrofitted	0	0	6	6	[b]
Switch tower	3[a]	6	6	15	3a
Switch tower, retrofitted	0	0	6	6	3b
Transformer	0	3	3	6	3c
Transformer, retrofitted	0	0	3	3	[b]
Corner or intersection	3	3	3	9	3d
Corner or intersection, retrofitted	0	0	3	3	[b]

[a] Not illustrated. Crossarm covers are identical to those of Tangent, 1 insulator per Ø, 2 level, retrofitted.

[b] Not illustrated. Jumper covers are identical to those of Terminal connection, 1 level, retrofitted.

but this was the most common pylon type surveyed (48%). Thus the configuration posed less risk per pylon than more complicated configurations with jumpers and terminal connections.

Carcass sizes ranged in length from 12 to 119 cm, and we found differences in the proportions of small, medium, and large birds under nonretrofitted and retrofitted pylons ($\chi^2 = 44.65$, df = 5,

Table 2. Summary statistics from χ^2 test for avian carcasses found under all pylon types during surveys in Hungary, January 2004 through December 2014. Ø denotes phase.

	Pylons surveyed		Carcasses found		χ^2 results		
Pylon configuration	Number	Percent	Observed	Expected	Percentage deviation	Standardized residuals	Risk score
Nonretrofitted							
Tangent, 1 insulator per Ø, 1 level	4,748	8.3	20	272	−93	−15	3
Tangent, 1 insulator per Ø, 2 level	27,805	48.4	1,174	1,584	−26	−10	3
Tangent, 2 insulators per Ø, 1 or 2 levels	4,621	8.0	494	262	89	14	6
Terminal connection, 1 level	2,547	4.5	419	147	185	22	9
Terminal connection, 2 levels	1,918	3.3	353	108	227	24	9
Switch tower	1,978	3.5	238	115	107	11	15
Transformer	1,162	2.0	101	64	58	5	6
Corner or intersection	2,335	4.1	357	134	166	19	9
Retrofitted							
Tangent, 1 insulator per Ø, 1 level	1,569	2.7	0	88	−100	−9	0
Tangent, 1 insulator per Ø, 2 level	7,098	12.3	56	403	−86	−17	1
Tangent, 2 insulators per Ø, 1 or 2 levels	647	1.1	27	36	−25	−1.5	4
Terminal connection, 1 level	332	0.6	19	20	−5	0	6
Terminal connection, 2 levels	184	0.3	8	10	−20	−1	6
Switch tower	169	0.3	2	10	−80	−3	6
Transformer	142	0.2	1	7	−86	−2	3
Corner or intersection	231	0.4	4	13	−69	−2	3
Total[a]	57,486	100.0	3,273	3,273	—		—

[a] Excludes 127 carcasses for which pylon configuration was not recorded.

Table 3. Summary statistics from χ^2 test for avian carcasses of all sizes found under all types of nonretrofitted pylons pooled and all types of retrofitted pylons pooled during surveys in Hungary, January 2004 through December 2014. Compare to Table 1 for analyses of various pylon types and Table 3 for analyses of various carcass sizes.

	Pylons surveyed		Carcasses found		χ^2 results	
Status of pylons	Number	Percent	Observed	Expected	Percentage deviation	Standardized residuals
Nonretrofitted	47,114	82	3,156	2,686	18%	9
Retrofitted	10,372	18	117	587	−80%	−19
Total[a]			3,273	3,273	—	—

[a] Excludes 127 carcasses for which pylon configuration was not recorded.

$P < 0.0001$). Smaller birds benefitted slightly less from retrofitting than did medium and large birds (Table 4). Across configurations, counts of conductors, jumpers, and terminal connections explained 61% of the variation in electrocution rates when considering all configurations, and 85% of the variation in electrocution rates when considering all configurations other than switch towers (Fig. 6), which incorporated elements of many other configuration types.

Discussion

Our primary objective in this study was to investigate the possibility that avian electrocution

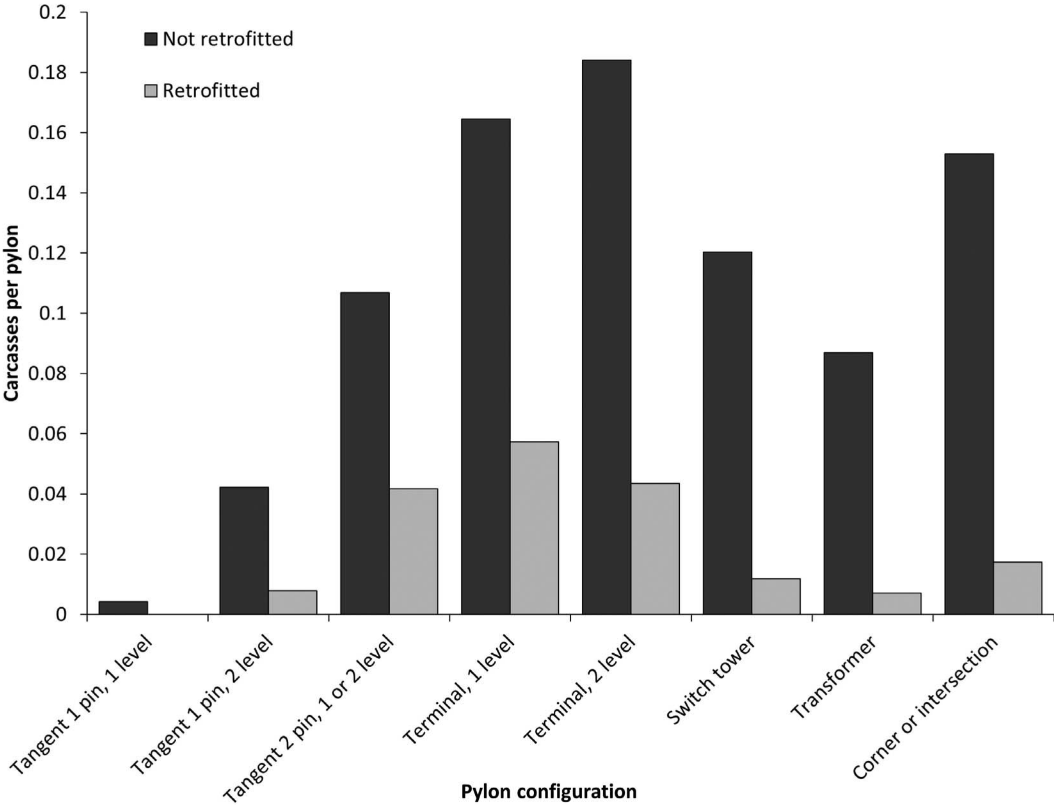

Figure 5. Comparisons of the average number of carcasses per pylon on nonretrofitted and retrofitted pylons surveyed in Hungary, January 2004 through December 2014.

Table 4. Summary statistics from χ^2 test for carcasses of various sizes (small ≤25 cm long, medium 26–49 cm long, large birds ≥50 cm long) found under nonretrofitted and retrofitted pylons during surveys in Hungary, January 2004 through December 2014.

	Carcasses found		χ^2 results	
Status of carcass	Observed	Expected	Percentage deviation	Standardized residuals
Nonretrofitted				
small	217	189	+15%	+2
medium	1,454	1,233	+18%	+6
large	1,343	1,139	+18%	+6
Retrofitted				
small	14	42	−67%	−4
medium	50	271	−82%	−13
large	46	250	−82%	−13
Total[a]	3,124	3,124	—	—

[a] Excludes 127 carcasses for which pylon configuration was not recorded, and 22 carcasses which could not be identified to species.

may pose a conservation concern in Hungary. The 3,400 birds of 17 species we found in association with electrical pylons met this goal. Carcasses were not formally necropsied in this study, but because in Hungary carcasses found in association with pylons have consistently been identified as electrocuted (Bagyura et al. 2004, Tóth 2010, Fidlóczky et al. 2014), even if some individuals included in these data died of other causes, overall numbers are sufficient to justify conservation concern. Because pylon configurations in Hungary are similar to those in nearby Croatia, Slovakia, and Bulgaria (MAVIR 2016), and because avian electrocutions occur widely in Europe and Asia, the electrocutions reported here should be viewed as informative to a conservation concern of regional importance. Specifically, birds migrating through or wintering in Eastern Europe may be encountering potentially dangerous pylons throughout much of their migratory or wintering

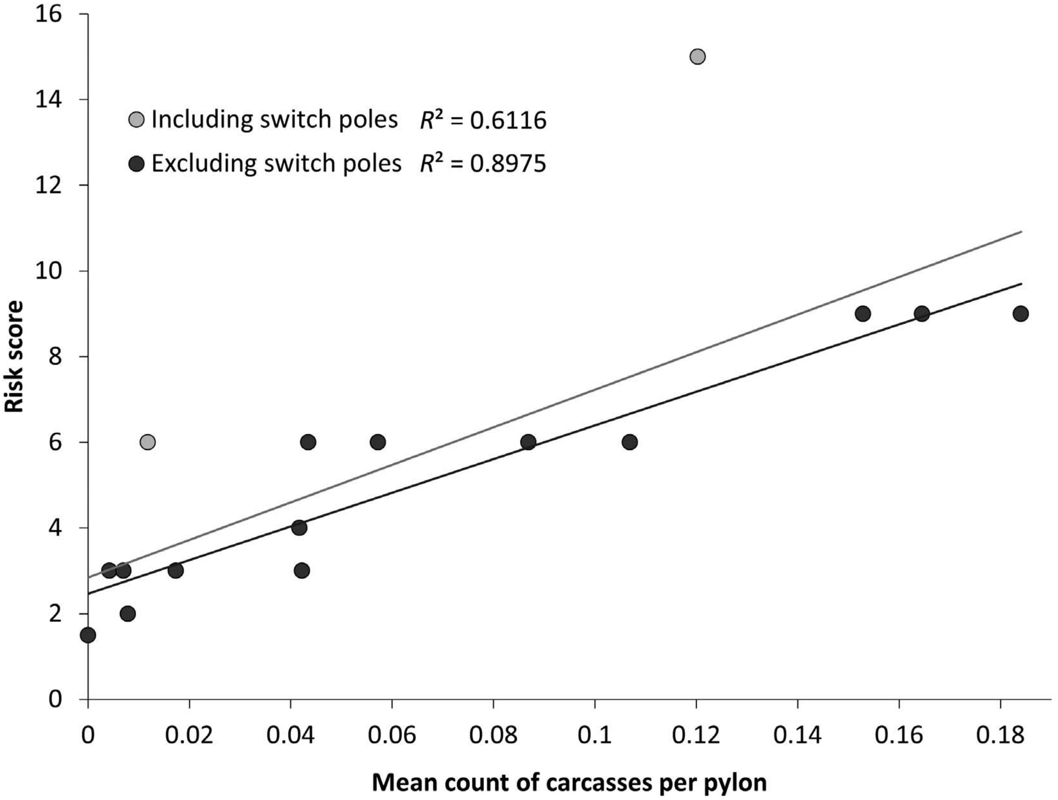

Figure 6. Comparisons of risk score and carcasses per pylon on nonretrofitted and retrofitted pylons surveyed in Hungary, January 2004 through December 2014.

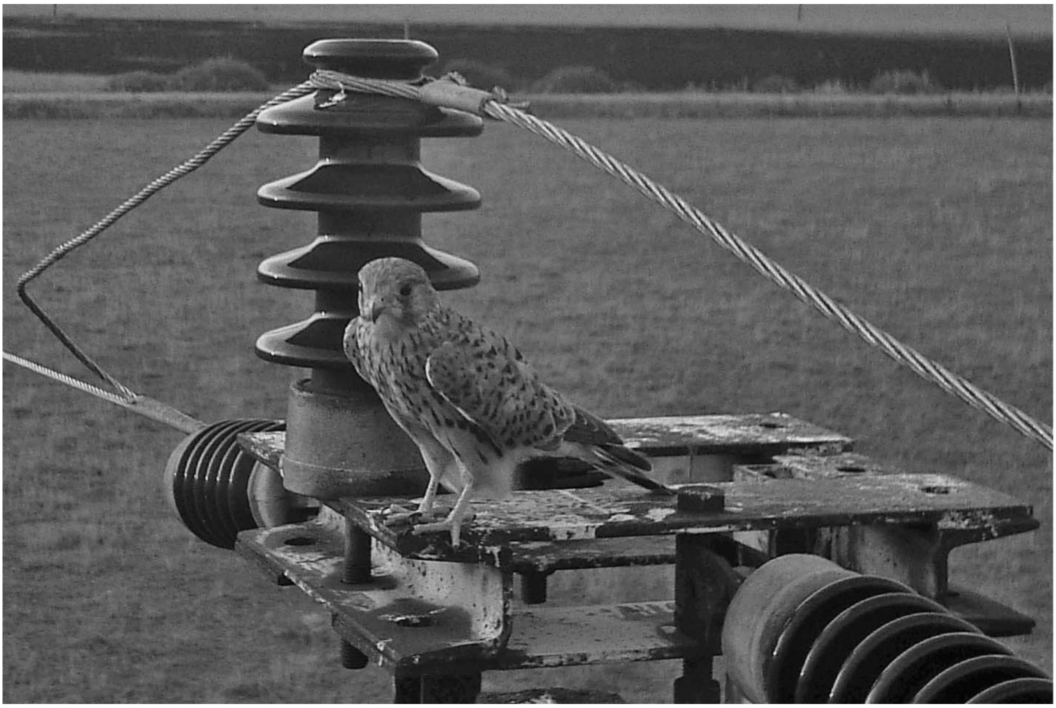

Figure 7. A Kestrel (*Falco tinnunculus*) perched on a grounded pylon-top directly below an energized distribution jumper. Photo P. Tóth.

ranges, potentially impacting populations breeding well north of our study area.

Conservation concern is especially relevant for threatened and endangered species because electrocutions could potentially contribute to or exacerbate declines of listed species. Our data included 4 species of concern: the vulnerable and declining Eastern Imperial Eagle (Demeter et al. 2005, Kovács et al. 2008, Birdlife International 2016a), the declining European Roller (Birdlife International 2016b), the globally endangered and decreasing Saker Falcon (Birdlife International 2016c), and the near threatened and declining Red-footed Falcon (BirdLife International 2016d). For 2 of these species, electrocution is known to be a primary agent of mortality in Hungary, causing 21% of the mortality of Eastern Imperial Eagles (Horváth et al. 2011) and 7–10% of juvenile mortality of the Saker Falcon (Nagy and Demeter 2006, Prommer et al. 2012, Kovács et al. 2014). Considering these observations, future electrocution research in Hungary may benefit from transitioning to more focused before-after-control-impact studies to shift electrocution research from correlative to causative and to focus mitigation on species that need it most.

Our secondary objectives in this study were to evaluate null hypotheses that all pylons were equally dangerous, and that retrofitting was equally effective for birds of all sizes. Both null hypotheses were rejected. Rather, consistent with numerous other studies and with models of electrocution risk (Bevanger 1998, Lehman et al. 2007, Ferrer 2012), avian electrocutions were disproportionately associated with more complex configurations. Our risk score was particularly effective in demonstrating these effects; lower risk scores were associated with fewer carcasses per pylon type and higher risk scores with more carcasses per pylon type. Similar risk scoring may be useful in other situations where personnel are not fully trained in the technical aspects of power line equipment. Avian electrocutions on non-retrofitted and on retrofitted pylons were especially associated with terminal connections. Terminal connections often included jumpers that passed over and were adjacent to grounded crossarms. Studies precisely modeling electrocution risk as a function of pole-top and pylon-top components have found the presence of grounding in proximity to energized jumpers such as these increases electrocution risk (Janss and Ferrer 1999, Dwyer et al. 2013). This risk can be mitigated in part by routing jumpers below crossarms (APLIC 2006), provided doing so does not create safety concerns for utility personnel climbing poles. Importantly, our findings are consistent with those of electrocution studies elsewhere (Spain, United States, India), even though our mechanism of identifying pylon types was relatively coarse.

Electrocution retrofitting was less effective for small birds than for larger birds, possibly because crossarm covers did not extend below conductors, allowing small birds to stand on grounded crossarms directly below energized conductors (Fig. 7). Medium and large birds would not fit in these locations, perhaps introducing a counterintuitive physiological constraint that reduced electrocution risk. Covering conductors with snap-on covers, a common mitigation method for protecting raptors from contact with primary conductors, may further reduce electrocution risk for small birds.

Although retrofitted pylons were associated with fewer carcasses, electrocutions persisted on retrofitted pylons because retrofitting did not fully separate energized from grounded components on any pylon type. Even small, subcentimeter gaps in retrofitting can allow electrocutions to occur (Dwyer et al. 2017), and the retrofitting measures used in Hungary included such gaps. Future retrofitting measures in Hungary should involve strategies to create the full 152 cm wide by 102 cm tall phase-to-ground separations recommended to reduce avian electrocution risk (APLIC 2006, Dwyer et al. 2015). To meet this goal, retrofitting mitigation should continue to include jumper covers but should also include covering conductors and terminal connections to eliminate exposed energized components adjacent to grounded components (APLIC 2006, Dwyer et al. 2015). Alternative pylon-top designs may also reduce avian electrocution risk.

Previous studies of raptor electrocution have not overtly relied on citizen science data, although many have benefitted from observations contributed initially by concerned citizens and then incorporated into datasets by researchers (e.g., Lehman et al. 2010). Consistent with Dwyer et al. (2013) and Harness et al. (2013), our findings suggest that nonprofessionals can be actively involved in documenting avian electrocutions. Future studies of electrocution should carefully consider benefits and drawbacks of including citizen scientists in addressing specific research questions, and when possible capitalize on the wealth of interest and energy volunteers have the potential to bring to conservation science.

Supplemental Material

Previously released data and analyses in Hungarian (Horváth et al. 2010 [Supplemental Material S1]), together with detailed lists of carcasses found (Supplemental Material S2, Tables S1 and S2) are available in an online Supplement. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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