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LETTER

Wired: impacts of increasing power line use by a growing bird population

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Abstract

Power lines are increasingly widespread across many regions of the planet. Although these linear infrastructures are known for their negative impacts on bird populations, through collision and electrocution, some species take advantage of electricity pylons for nesting. In this case, estimation of the net impact of these infrastructures at the population level requires an assessment of trade-offs between positive and negative impacts. We compiled historical information (1958–2014) of the Portuguese white stork *Ciconia ciconia* population to analyze long-term changes in numbers, distribution range and use of nesting structures. White stork population size increased 660% up to 12000 breeding pairs between 1984 and 2014. In the same period, the proportion of nests on electricity pylons increased from 1% to 25%, likely facilitated by the 60% increase in the length of the very high tension power line grid (holding the majority of the nests) in the stork's distribution range. No differences in breeding success were registered for storks nesting on electricity pylons versus other structures, but a high risk of mortality by collision and electrocution with power lines was estimated. We discuss the implications of this behavioral change, and of the management responses by power line companies, both for stork populations and for managers.

1. Introduction

Overhead power lines are increasingly widespread across many regions of the planet. These linear infrastructures are known to have negative impacts on bird populations, mainly through collision and electrocution (e.g. Loss *et al* 2014, 2015, Ogada *et al* 2015). On the other hand, power lines may provide benefits for several bird species (e.g. storks, raptors, corvids), as wires and pylons may be used as perches or nesting sites (Morelli *et al* 2014, Mainwaring 2015). This creates a paradox for conservation, since positive and negative impacts of the use of power lines may co-exist (Tryjanoski *et al* 2014) and the estimation of the net impact of these structures at the population level will have to take these trade-offs into account.

The white stork *Ciconia ciconia* Linnaeus 1758 is an interesting case study to address the pros and cons of power line use, as this iconic species is associated with human infrastructures and often uses electricity pylons for nesting (Janss 1998, Infante and Peris 2003, Kaluga *et al* 2011). A few studies have suggested that their breeding performance may be negatively affected when nesting on these structures compared to natural sites or other types of anthropogenic structures, due to the occupation of these nesting sites by younger inexperienced individuals, disadvantageous microclimatic conditions or exposition to electromagnetic fields (Janiszewski *et al* 2015, Vaitkuvienè and Dagys 2014). In addition, storks are particularly prone to mortality by collision and electrocution with power lines (Schaub and Pradel 2004, Kaluga *et al* 2011), due to their large body size (Bevanger 1998). Power lines may therefore represent an ecological trap by attracting storks to nest in locations that ultimately reduce their fitness (Mainwaring 2015). From the human perspective, the use of pylons by storks has implications for the management of power lines, as storks and their nests are often the cause of power outages (disruption of energy transport) with negative impact on the electricity users in all sectors of the economy (Maricato *et al* 2016).

In this paper we aimed to evaluate the pros and cons of the use of electricity pylons by the Portuguese white stork population. We compiled historical (1958–2014) information on population size and range distribution trends, and on the use of different nesting structures. In addition, we tested whether breeding success differed between storks nesting in electricity pylons *versus* other structures, and also gathered information on the risk of electrocution and collision in the country. We found that this white stork population is increasingly using electricity pylons, and discuss the implications of this changing behavior, both for the management responses by power line companies and for the species.

2. Methods

2.1. Population size and distribution range trends

National white stork census data were gathered for Portugal for the period 1958/59–2014, from Santos Júnior (1961), Borges de Carvalho (1977), Candeias and Araújo (1989), Rosa *et al* (1999), Rosa *et al* (2005) and Encarnação (2015). Information on stork occurrence at municipal level (figure S1 available at stacks.iop.org/ERL/12/024019/mmedia) for each census was also compiled and organized in a Geographic Information System (GIS). This information was used to quantify the distribution range (km^2) in each time period.

2.2. Nesting site selection and the use of power lines

The evolution in the proportion of occupied nests on different types of structures—trees, buildings (chimney, roofs, ruins, churches), poles (including dedicated poles i.e. man-made poles equipped with an artificial nest platform, low to high voltage power line pylons, and telephone poles) and other structures (e.g. cliffs)—was also extracted from the above mentioned reports.

The power line network in Portugal comprises of a very high voltage (150–400 kV) transmission grid managed by the REN (Redes Energéticas Nacionais) company, and other distribution grids of varying voltage (high: 60–120 kV, medium: 6–45 kV and low: 220–400 V) managed by the EDP (Energias de Portugal) company. Because of structural differences (size, building materials, shape) the suitability of pylons to hold stork nests usually increases with voltage. Consequently, pylons of the REN grid are large structures that have a much higher capacity of holding several stork nests (up to more than 30), compared to pylons of the EDP grid.

Whilst information on the use of power line pylons coming from national stork counts did not include voltage information prior to 2004, in 2004 and 2014 nests on pylons were classified separately as low, medium or high/very high voltage. More detailed information was gathered from REN, whose power line pylons currently concentrate most of the stork nests, as this company has spatially-explicit historical data of the very high voltage grid and carries out yearly counts of storks nests on their pylons since the 1990s. This information was incorporated into the GIS, in order to estimate the network length and the number of pylons overlapping the white stork distribution range across time. In addition, nest counts made by REN were used to estimate the proportion of the total population nesting in REN pylons. As these counts did not separate occupied from unoccupied nests, we estimated the number of occupied nests using the proportion of occupied nests counted at national level for the same years (respectively 88.5%, 93.7% and 95%, for 1994, 2004 and 2014).

2.3. Productivity in power line pylons versus other nesting structures

In order to compare productivity for storks nesting in different structures, productivity data were taken from a sample of 743 nests from eight different regions spread over the main distribution range (figure S1) in Portugal. Each nest was monitored monthly, starting in late February, over one breeding season (either in 2009 or 2014). Productivity, expressed as the number of fledged young (over 50 days old) per monitored nest, was compared across structure type using a generalized linear mixed model (GLMM) with a Poisson distribution and log-link function, implemented in package 'lme4' (Bates *et al* 2015). Region was included as a random effect to account for lack of independence due to regional/yearly variations in habitat availability that may affect productivity. We assessed the power of the obtained model, i.e. the likelihood of detecting a decrease in productivity when nesting on electricity pylons assuming this effect is real, through a Monte Carlo simulation based power analysis (1000 simulations; z-test) using package 'simr' (Green and MacLeod 2016). We estimated the power of our model for detecting three specified effect sizes of decreased productivity in electricity pylons (−0.1, −0.5 and −1 fledglings per nest, compared to the overall mean), all biologically plausible values considering the measured range in this variable. During

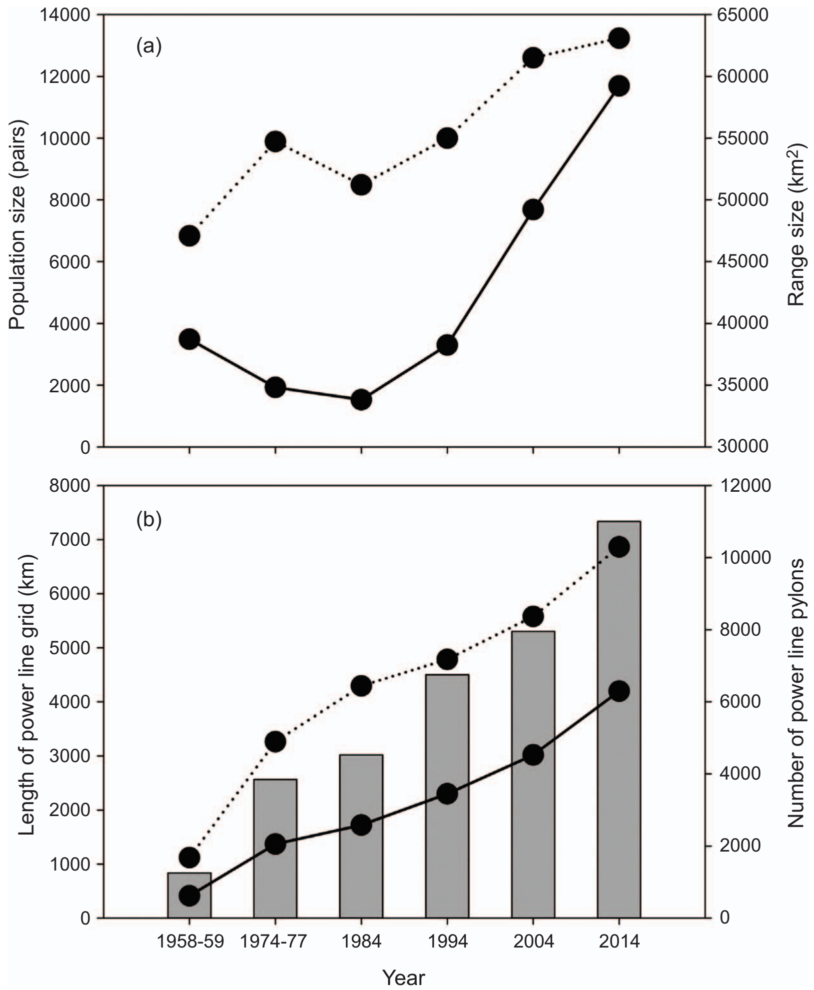

Figure 1. (*a*) White stork *Ciconia ciconia* population size (number of pairs) (solid line) and distribution range (km^2) (dotted line) in Portugal during the 1958/59–2014 period. (*b*) Total length (km) of the very high voltage power line network in Portugal (managed by the REN company) (dotted line), length within the white stork's distribution range (solid line), and estimated number of REN power line pylons available within the distribution range (bars) during the 1958/59–2014 period.

simulations, random effects were set at their estimated values. All analyses were conducted in the R statistic environment (R Development Core Team 2014).

2.4. Mortality by collision and electrocution

Between 2003 and 2005, the impact of the very high (REN), and high and medium tension (EDP) voltage lines on overall bird mortality in Portugal were assessed for the first time. This was carried out in the scope of two protocols between power line companies (EDP and REN), the Institute for Nature Conservation and non-governmental conservation organizations (Quercus and SPEA-BirdLife Portugal) (details in Infante *et al* 2005 and Neves *et al* 2005). A total of 531 power line sections (428 from the EDP grid and 103 from REN), each 2 km long, were distributed across the whole country in areas identified as important for birds. Each section was visited 4 times (roughly corresponding to the breeding season, post-breeding, migration and wintering) during one year. Carcass searches were performed by 1 to 3 observers in a 20 m strip beneath the lines (and in a 5 m buffer surrounding each pylon). All carcasses found were removed to avoid double counts. Cause of death was assigned to collision or electrocution based on observed injuries and carcass location in relation to pylons. The number of dead storks was corrected for scavenger bias, search bias, habitat bias, and crippling bias, following Bevanger (1999) (table S1), to estimate real mortality due to collision and electrocution. The applied correction factors are relatively crude, compared with currently available methods and field protocols, mainly related with scavenger bias, that minimize estimation errors (e.g. Huso 2011), but we assume the results provide a first estimate of the order of magnitude of the importance of mortality caused by power lines on white storks.

3. Results

3.1. Population size and distribution range trends

Population trends of the Portuguese white stork population showed a decrease in the 1958–1984 period, followed by a fast increase up to almost 12000 breeding pairs in 2014 (figure 1(*a*)). During the

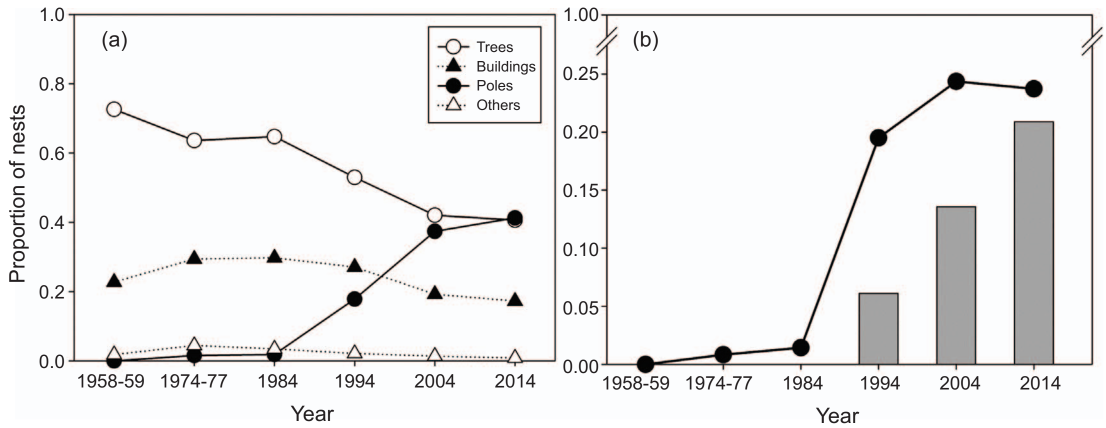

Figure 2. (*a*) Proportion of white stork *Ciconia ciconia* nests in each type of structure in Portugal, during the 1958/59–2014 period. For each year data were gathered from samples of nests covering at least 50% of the total breeding population (table S2). Poles include dedicated poles, telephone poles and power line poles. (*b*) Proportion of total number of occupied white stork nests located in power line pylons (line) and estimated fraction located in very high voltage (REN) pylons (grey bars) since 1994 (when these data started being available).

1984–2014 population recovery period, population size increased 660%, whereas distribution range increased only 23% (figures 1(*a*) and S2). In 2014, stork range occupied ca. 70% of the country's area.

3.2. Nesting site selection and the use of power lines

During 1958–2004, trees were the main structure used for nesting. As the population increased after the 1980s, all the major structure types were increasingly used, but the rate of increase in pole use was much faster than in other structures (table S2). Consequently, the proportion of nests in trees decreased steadily, whereas the proportion of nests in different types of poles increased fast so that in 2014 poles were the main substrate used (figure 2(*a*)). The main type of poles used by storks were power line pylons (over 60% of the total, for 2004 and 2014), mainly high/very high voltage (table S3). Consequently, the proportion of the Portuguese population nesting on power line pylons increased quickly after 1984, to reach almost 25% of the total in 2004 and 2014 (figure 2(*b*)). This increase was most noticeable in the pylons on very high voltage (REN) power lines, accountable for an increasing proportion of the total population nesting in electricity pylons since data were available (starting in 1994; figure 2(*b*)).

During the 1958–2014 period, the total length of the very high voltage power line grid (managed by REN) increased, both at the country level and within the stork distribution range (figures 1(*b*) and S2). As a result, the number of REN pylons potentially available for stork nesting increased almost tenfold, from 1256 to 11002, along the studied period (figure 1(*b*)).

3.3. Productivity in power line pylons versus other nesting structures

Overall productivity (mean ± standard error) was 1.88 ± 0.05 fledglings per nest (range = 0–6, median = 2). After controlling for the effect of region, there was no evidence of differences in stork productivity between nests located on electricity pylons *versus* other structures (p-value = 0.997; table S4), in spite of the trend for lower values in buildings (figure S3). Power analysis showed that this model only had adequate power (over 80%) to detect negative impacts on productivity due to nesting in power lines, in case they existed, if these were in the range of an average decrease of 0.5–1 fledglings per nest (95% confidence intervals for estimated power: 10.7%–14.9%, 61.8% –67.8%, and 99.6%–100%, respectively for a decrease of −0.1, −0.5 and −1 fledglings per nest).

3.4. Mortality by collision and electrocution

The white stork was the bird species with highest number of registered deaths in one year, both in medium and high voltage (EDP) lines (137 individuals by electrocution and 24 by collision) and in very high voltage (REN) lines (50 individuals by collision). For the latter, mortality occurred mainly during the breeding and post-breeding periods and was more prevalent in juveniles. After applying the correction factors, a total of 420 storks was estimated to be killed every year in the sampled transects in EDP lines (0.49 birds km yr^{-1}), and 224 storks in REN lines (1.09 birds km yr^{-1}). In the case of REN power lines, a direct extrapolation to the total length of the grid within the stork distribution range in 2004 yields an estimated 3282 white stork fatalities. This corresponds to 11.0% of the total population during the breeding season, assuming an overall mean productivity of 1.88 fledglings per nest for a total population of 7684 pairs in 2004.

4. Discussion

4.1. Population size and distribution range trends

In spite of the likely underestimation of the white stork population and distribution range in Portugal in 1958/59, as the count was based mainly on enquires and there were gaps in geographic coverage, the observed trend in the 1958–2014 period reflects the overall European tendency for decades of decline followed by an increase of white stork populations after the 1980s (Schulz 1999). This increase has been particularly large in the Iberian Peninsula, due to improved climatic and feeding conditions both in the wintering range (West African Sahel) and in Iberia, where milder winter temperatures and increased food availability (caused by increased areas of rice fields, open garbage dumps, and the introduction of the exotic red-swamp crayfish *Procambarus clarkii*) have increased the proportion of resident storks and the survival rate (e.g. Schulz 1999, Tortosa *et al* 2002). In spite of the large population increase, distribution range did not change substantially.

4.2. Nest site selection: increased use of power lines for nesting

On average, over the 1958–2014 period, trees were the main structure used by the Portuguese white stork population for nesting. However, stork nests have been increasingly concentrated on different types of man-made poles, electricity pylons in particular, so that ca. 25% of the Portuguese population is currently nesting on these structures. There are four main non-exclusive hypotheses for explaining this progressive change: (i) increased pylon availability in the white stork distribution range, due to growing length of the power line grid. The total length of the grid of very high voltage REN lines in the stork distribution range increased tenfold in the 1950–2014 period. Data from EDP (personal communication) shows a twofold increase in the length of their national high voltage grid in the 1980–2014 period. The increased availability of electricity pylons may be particularly important close to areas providing good feeding conditions and without alternative nesting structures; (ii) increased availability of nesting platforms and dedicated poles made available by electricity companies to minimize the risk of power outages; (iii) a possible degradation in the suitability of buildings or trees used for nesting. Other studies have shown that changes in roof structure may decrease their suitability for storks (e.g. Schulz 1999). Similarly, the decreased availability of ruins or suitable large trees for building nests is a possibility that needs testing; (iv) a preferential selection for these structures because they provide fitness benefits such as reduced pressure from predators or a better productivity (Schulz 1998, Janiszewski *et al* 2015). Independently of the drivers, this trend for the increased use of man-made poles as nesting structures by storks seems to be widespread across Europe (Tryjanowski *et al* 2009, Janiszewski *et al* 2015).

Electricity poles holding very high voltage power lines (managed by REN) supported an increasing share of the total white stork nests. This is a consequence of: (i) the fact that these pylons are large structures capable of holding several nests each, and storks often show colonial behavior in the Iberian Peninsula (Schulz 1998); (ii) the management policy of medium/high voltage lines followed by EDP, to decrease power outages, which has consisted of removing nests located in their pylons after 2003, contributing to the decreased proportion of nests in these pylons (25% to 7% during 2004–2014; table S5). As a consequence, remaining nests on electricity pylons are increasingly concentrated on REN lines.

4.3. Conclusions: implications for stork conservation and power line management

Current trends show an increasing proportion of the Portuguese white stork breeding population nesting on power line pylons, particularly very high voltage lines. Our results indicate that this change did not have an impact on the stork breeding success in Portugal, although this should be taken with caution due to the moderate power of the productivity model. Previous research found conflicting results, with evidence of either no impact (e.g. Tryjanowski *et al* 2009) or a negative impact on productivity (Janiszewski *et al* 2015) as a consequence of nesting on electricity pylons. Future studies should further clarify this aspect, including evaluating the potential impacts of electromagnetic fields on nesting storks (Vaitkuvienè and Dagys 2014).

Even if there are no significant effects of power line nesting on productivity, an increased risk of mortality by collision and electrocution is expected as the power line grid expands. Our preliminary estimate of 11% of the Portuguese population (mainly young birds) being killed in REN lines is probably an overestimate as it results from extrapolation from a sample of power line sections located within areas important for birds and including sites with high densities of breeding storks. However, this estimate needs to be summed up with the one for the much larger grid (see below) of medium and high tension lines EDP lines (in spite of an estimated lower mortality per unit length), in order to evaluate the overall impact of power lines in the stork population. This will be dependent on the availability of data on the length of the EDP grid within the stork range and the number of nests on pylons of this grid. Existing studies show that white stork annual mortality rates due to power lines are much higher in juveniles (10%–25%) than adults (1%–10%) (Garrido and Fernández-Cruz 2003, Schaub and Pradel 2004, Kaluga *et al* 2011) and our preliminary incomplete estimate suggests a likely impact towards the upper limit of these intervals.

The population-level consequences of power line induced mortality and of the trade-offs between positive and negative impacts needs to be clearly addressed in future studies, and will require data-demanding (e.g. survival rates, dispersal, mortality by other causes) population-level simulations that are out of the scope of the current paper. However, a

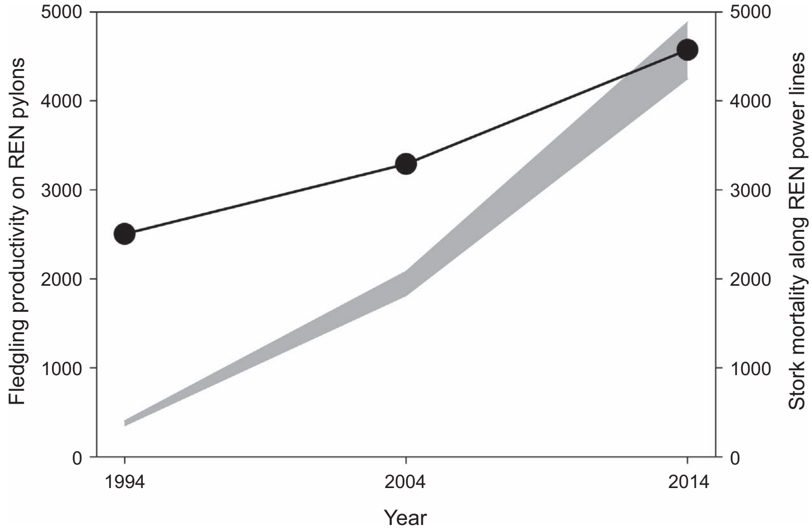

Figure 3. Evolution of the estimated contribution of the very high tension power line (REN) grid in Portugal as a source/sink of individuals to the white stork *Ciconia ciconia* population. For each year, the number of individuals lost due to mortality by collision (black line) was derived from the existing length of the power line grid within the stork distribution range multiplied by the (assumed constant) estimated mortality impact of 1.09 birds km yr^{-1}. The number of individuals (fledglings) contributed to the population (shadowed area) was estimated from the number of occupied nests in the REN grid multiplied by the (also assumed constant) estimated productivity of nests in this type of infrastructure (mean ± 95% confidence interval = 1.87 ± 0.13 fledglings per nest).

preliminary estimate of the contribution of the REN power line grid to mortality and productivity suggests that, through time, the number of individuals entering the population has been progressively compensating the increased mortality due to this infrastructure (figure 3). This is a consequence of the fact that the length of the power line grid in the stork's range (contributor to mortality) increased much slower (1.8 times) than the number of nests in power line pylons (contributor to productivity) (12.1 times). This trade-off is likely distinct from the one of EDP distribution lines, as the extent of their grid is much larger (over 5000 km in high tension and 45000 km in medium tension, since 1994; EDP pers. comm.) and the number of nests in their pylons is becoming proportionally smaller (tables S3 and S4).

From the power line company perspective, an increased use of pylons by storks implies an increased risk of power outages and a need for impact mitigation measures. Typical measures include applying technical changes to poles and wires to reduce collisions or electrocutions, the use of nesting deterrent devices, undertaking nest relocations or removal, and providing alternative dedicated pole platforms for nests (e.g. Barrientos *et al* 2011, Kaluga *et al* 2011, Maricato *et al* 2016). The current REN policy includes translocating nests from risk areas to dedicated nesting platforms in safe areas of the pylons, followed by the installation of anti-nesting devices to avoid storks coming back to previous nest sites. From 1999 to 2015, the number of anti-nesting devices installed by REN increased from 347 to 8233, and the number of installed nesting platforms went up from 500 to 3143 (personal communication). The number of translocated nests in the period 1999–2012 was 1347. However, this management approach has been successful in terms of avoiding power outages, as the annual incident rate reported by REN (number of outages per 1000 nests) has been steadily declining from 739 in 1993 to 13 in 2014.

Mainwaring (2015) describes the use of man-made structures by nesting birds as a possible win-win situation. This seems to be currently the case with the white stork in Portugal, as companies managing power line grids show a biodiversity-friendly attitude matching their environmental and social responsibility policies, promoting their image to the public and being able to keep negative impacts and mitigation measures at acceptable costs. Negative impacts on the white stork population are not visible, as there is an ongoing notorious population increase. But if the white stork population continues to increase, as well as its use of an also expanding power line grid in Portugal and elsewhere in Europe, company costs in impact mitigation measures will probably increase, eventually representing a significant investment in financial and human resources. Furthermore, the expected increased mortality by collision and electrocution due to the continuing growth of the power line grid might ultimately have impacts on the stork population trends.

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