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Environmental determinants of unscheduled residential outages in the electrical power distribution of Phoenix, Arizona

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ABSTRACT

The sustainability of power infrastructures depends on their reliability. One test of the reliability of an infrastructure is its ability to function reliably in extreme environmental conditions. Effective planning for reliable electrical systems requires knowledge of unscheduled outage sources, including environmental and social factors. Despite many studies on the vulnerability of infrastructure systems, the effect of interacting environmental and infrastructural conditions on the reliability of urban residential power distribution remains an understudied problem. We model electric interruptions using outage data between the years of 2002 and 2005 across Phoenix, Arizona. Consistent with perceptions of increased exposure, overhead power lines positively correlate with unscheduled outages indicating underground cables are more resistant to failure. In the presence of overhead lines, the interaction between birds and vegetation as well as proximity to nearest desert areas and lakes are positive driving factors explaining much of the variation in unscheduled outages. Closeness to the nearest arterial road and the interaction between housing square footage and temperature are also significantly positive. A spatial error model was found to provide the best fit to the data. Resultant findings are useful for understanding and improving electrical infrastructure reliability.

1. Introduction

Electrical power is a basic public service. The reliability of electrical power is important because many other infrastructures are directly dependent on it. Power interruptions may, for example, compromise transport and communications systems, and other emergency and security services [1]. Power interruptions are also inconvenient and costly to both commercial and residential consumers, precluding the use of lighting, computers, refrigerators, and HVAC systems among others [2]. A study of expected damage costs in the wake of the major blackout in the Northeastern U.S. and Canada in 2003 identified costs to three categories of consumers: residential, commercial and industrial, and what the authors termed 'wider infrastructure'—the ability of municipal, state and federal authorities to maintain essential public services [3]. The study concluded the costs incurred by residential users accounted for about $1.6 billion per year.

The reliability of power infrastructures is a measure of their capacity to function over the range of expected environmental conditions. Most existing studies of electrical reliability explore cascading blackouts at a national or regional scale. For example, Hines et al. [4] study regional blackouts in the U.S. using the Disturbance Analysis Working Group (DAWG) database from the North American Electrical Reliability Council (NERC) and investigate the different causes of regional blackouts. In this paper we consider a different problem: the role of interactions between distinct environmental and infrastructural conditions in determining the average reliability of the electric power distribution infrastructure. There are many studies on the vulnerability of infrastructures of this type [5,6]. However, the effect of interacting environmental and infrastructural conditions on the reliability of power distribution systems remains under-researched [7–9]. While the impact of individual environmental conditions such as animals, trees, sand/dust, lightning, earthquakes, hurricanes, and ice storms on power reliability has been well documented [10–19], interactions between them have not. Analysis of responses to individual events such as hurricanes provides some insight into the reliability of the electrical distribution system, but unless it controls for the effect of interactions between the event and other environmental conditions, the results may be misleading. In urban areas, for example, outages in residential power frequently occur because of interactions between biophysical, environmental and infrastructural conditions. Storm winds cause vegetation to come into contact with electrical

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distribution lines. Poles, vegetation, and water bodies attract birds that interfere with overhead lines through collision, nesting, excrement, and other activities and so on.

In this paper, we consider the factors that affect residential power reliability in the urban region of Phoenix, Arizona focusing on environmental conditions, the electric power distribution infrastructure, and interactions between the two. We model electric interruptions using outage data for the years 2002–2005 obtained from Arizona Power Supply (APS), a local utility. Estimations were conducted using least squares regression, generalized linear regression, and spatial regression. We consider all unscheduled incidents where voltage falls to zero. These include momentary outages that persist no longer than a few seconds and blackout incidents that persist longer than a few minutes. We focus on the distribution system (the supply system of energy from distribution substations to end users) rather than the transmission system (the supply system of high voltage bulk energy from a generating source to distribution substations) since we are interested in environmental interactions. The electrical distribution system is denser and covers a greater geographical area than the transmission system. It therefore operates within a wider range of environmental conditions, and is more exposed to hazardous environmental events and conditions. It also accounts for most of the interruptions experienced by electricity consumers [7,20]. We consider a number of infrastructural characteristics including feeder type (overhead or underground), age associated with feeder type, closeness to other major infrastructures, together with a number of environmental characteristics such as proximity to desert areas, vegetation, and bird abundance. Our results should be useful for understanding and improving residential electrical infrastructure reliability.

The structure of the paper is as follows. The next section offers a description of the recorded causes of unscheduled outages in the electrical power distribution system. Section 3 details the data and methods used in the analysis. It describes an outage model that is calibrated specifically for Phoenix, Arizona, but is sufficiently general in structure to be applied to other urban areas. Section 4 describes our results. These are then discussed in Section 5. A final section offers our conclusions.

2. Background

Reliability events comprise any deviation from a pure 60-cycle per second alternating current supply, typically at 120 V for residential customers or 480 V for commercial and industrial customers. In practice, however, reliability events at the customer level are taken to be interruptions (incidents where voltage falls to zero) captured in any of the main reliability indices: The System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), or the Momentary Average Interruption Frequency Index (MAIFI) [21]. An interruption is a complete loss of power supply experienced directly by customers. Causes can range anywhere from errors in generation to component failures in the distribution system [22,23]. Interruptions are often caused by outages, or when a component of the electrical infrastructure is not available to perform its function [20,24]. However, outages do not necessarily lead to interruptions experienced by customers [25]. Outages are either scheduled in advance by utility companies or are forced by unscheduled events. In this paper, we only consider unscheduled outages in the distribution system.

Unscheduled power outages are caused by distribution equipment failure induced by factors typically classified as 'environmental' or 'non-environmental' [7,20]. Non-environmental factors include innate problems in the equipment and its use. Age is a contributing element to electrical equipment failure as with most mechanical equipment [26]. With increasing age, power distribution systems deteriorate becoming more vulnerable to disruption. Overloading distribution lines is another important non-environmental factor causing outages [27]. Power supply lines have limited carrying capacity. When demand exceeds the supply limit, distribution lines overload causing overheating which can lead to sagging, reducing ground clearance, potentially leading to contact with proximal vegetation and intermittent failure. Proper demand forecasting and reliable software support systems help avert problems of overloading. Otherwise, overloading can lead to outages in the distribution system if load shedding is not conducted [28]. Overloading also accelerates insulation age thereby reducing the physical lifespan of the distribution infrastructure [29].

Equipment failure also occurs when deteriorating components interact with adverse 'environmental' conditions. These include both environmental events such as electrical, rain, winter, wind or dust storms, and interference by vegetation or animals [20]. Weather-related events such as lightning, extreme temperatures, tornadoes, ice storms, cyclones, and flooding are major contributors to power outages [16,20,30–32]. Fire, especially in the presence of combustible material, can cause electrical faults [33]. High ambient temperatures can reduce distribution efficiency by reducing the transducer's ability to dissipate heat to the environment [34]. Fire, lightning, or heat waves may exacerbate the heat induced by overloading, exemplifying a potentially important interaction. Overhead distribution components can be affected by lightning primarily through direct flashes and less frequently through indirect flashes [20,35]. In contrast, extremely cold temperatures can lead to icing of distribution components such as insulators and reducing electrical performance [36]. Flooding and 'water treeing' (where water penetrates insulation) can short-circuit underground distribution lines while excessive rain may short-circuit overhead lines [37]. Electrical infrastructure can also be impaired depending on its location with respect to an earthquake's impact radius [19].

Interactions exist between weather events and other environmental conditions. Trees unduly close to overhead lines frequently induce adverse interfaces [38]. A tree outside a right-of-way that can fall within five feet (or about 1.524 m) of a distribution line is considered to be a 'danger tree' [39]. The effect of vegetation on power distribution reliability ranges from brief contacts that cause faults by bridging two conductors, to tree fall that brings overhead lines down [40,41]. Growing branches can intrude upon conductors, animals can move branches into conductors, and dead trees can fall interfering with equipment [42]. Tree-to-line contact is most likely to occur if combined with a severe weather event. Tornadoes, hurricanes, and major thunderstorms are accompanied by high wind speeds that cause branches to sway into power lines and, in the worst case, cause trees to fall across lines [43]. In the Northeast U.S., for example, it has been estimated that between 20% and 50% of unscheduled outages are due to vegetation interference with overhead power lines [13].

Other species also come into contact with both overhead and underground power distribution cables, frequently causing interruptions [44]. Squirrels, birds, snakes, rats, mice, gophers, ants, raccoons, and other large animals cause interruptions on a regular basis [10,11,14,20,45,46]. Birds, including raptors (large birds of prey) and other smaller species, are a common cause of 'animal' faults on distribution systems, substations, and transmission systems due to nesting, excrement, and other activities [20]. Raptors are attracted to poles that truss overhead lines [47]. Birds in flight can also collide with overhead lines causing bird electrocutions and reduced electrical reliability. Bird electrocutions are most commonly

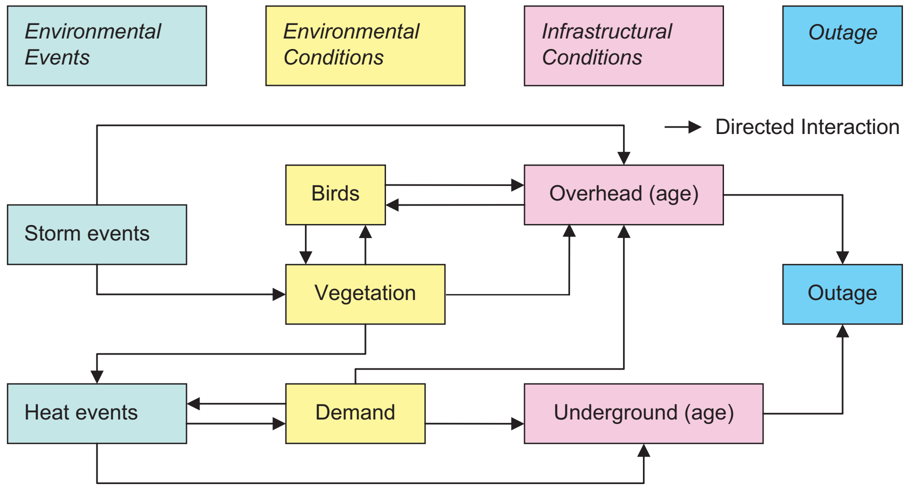

Fig. 1. Outage diagram of the interactions between environmental events, environmental conditions, and infrastructural conditions.

associated with distribution lines instead of transmission lines [48]. Interactions affecting electrical outages are illustrated in Fig. 1: environmental events such as storms or heat events can interact with environmental conditions such as vegetation, with differential effects depending on the type and age of infrastructure.

There is also an interaction between environmental conditions, environmental events and demand. Heat events affect reliability through their effect on demand via increased usage of HVAC systems, and the positive feedback of increased usage of HVAC systems on ambient temperature. At the same time, feedbacks of that kind can be moderated by vegetation, since vegetation generally cools ambient temperatures. In this paper, however, we do not consider such indirect interactions.

3. Methods and data

3.1. Study area

The study area comprises a central transect within the municipal boundaries of the City of Phoenix, Arizona stretching from the Sky Harbor Airport in the South to the Carefree Highway (SR 74) in the North. Phoenix accounts for about 35% of the metropolitan area's population and is the 6th largest city in the U.S. [49]. Phoenix represents a good case study for three reasons. First, the reliability of electrical power in Phoenix (and the U.S. in general) is quite variable relative to other developed countries such as Sweden [50]. Second, Phoenix has a unique environment. Phoenix is situated in a desert and yet has a diverse and frequently highly vegetated urban-biophysical environment. It is also served by range of electrical distribution infrastructures. Roughly half of Phoenix is served by electricity distributed through overhead lines and half by underground cables. Finally, greater Phoenix is still one of the most rapidly growing metropolitan areas in the nation. Thus, future electrical reliability planning is important for both current and future residents. The Phoenix metropolitan area's power is supplied by two major sources, APS and Salt River Project (SRP). Outage data were provided by one of these, APS. The areas within the municipal boundaries of the City of Phoenix serviced by SRP were accordingly excluded.

3.2. Environmental power reliability factors for Phoenix, Arizona

Phoenix is situated in the Sonoran Desert. It follows that locational factors causing unscheduled residential power interruptions are contingent on the desert and urban environments. The city has an arid climate with extremely hot summers and mild winters. Compared with the rest of the U.S., it experiences relatively little wind [51]. Nor does it experience frequent storms, or the high levels of precipitation that affect cities on the East coast. On average, Phoenix receives around 8 in of rainfall per year [52], and has relatively low keraunic levels, meaning thunderstorms and lightning are infrequent. Ice storms, hurricanes, and tornadoes are all rare in Arizona. The effects of tropical storm winds stemming from low-pressure systems in the Pacific are expected to reach Arizona once every five years on average [53]. It follows that storm and storm-related (e.g. vegetation) damage would be expected to be less significant causes of outages in Phoenix than in the East. Although some lightning and thunderstorms occur during the late summer monsoon season (July–September), lightning storms are also relatively rare in the West and would be expected to have a relatively small impact on power reliability in Phoenix.

The majority of Arizona's built environments are not affected by the seismic activity of the circum-Pacific belt. Residents within Phoenix rarely experience tremors associated with earthquakes. Although destruction to the built environment has occurred near Flagstaff and along the Western and Southern borders of Arizona in the past, no earthquake has ever caused deaths or injuries in the recorded history of Arizona [54].

Potentially important risk factors to the reliability of the power distribution grid in Phoenix include overloads associated with episodes of extreme heat as well as sandstorms, and excessive amounts of dust. Temperatures can reach up to 49 °C during the summer months potentially resulting in overloading of power distribution lines due to the energy needed to power air conditioning units. Additionally, the natural desert environment generates wind-borne dust and sand that interferes with insulators, reducing effective distribution potentially resulting in flashover outages [15,55]. The desert environment effect is worst during sand storms, when strong winds lead to sand particle saltation at high speeds occasionally leading to suspension [15]. Many places in Phoenix have flood irrigation. Trees are abundant in areas where flood irrigation is predominant, and potentially interact with birds, wind and overhead lines (especially when lines sag during overloading and overheating events).

Automobile traffic and construction digs, as noted by [20,45], are relatively smaller contributors to power outages than storms, trees, lightning, and animals in general. However, polycentric, low-density cities such as Phoenix are automobile-oriented, so traffic accidents are a potentially important factor in overhead line outages. In addition, Phoenix's rapid urban growth means

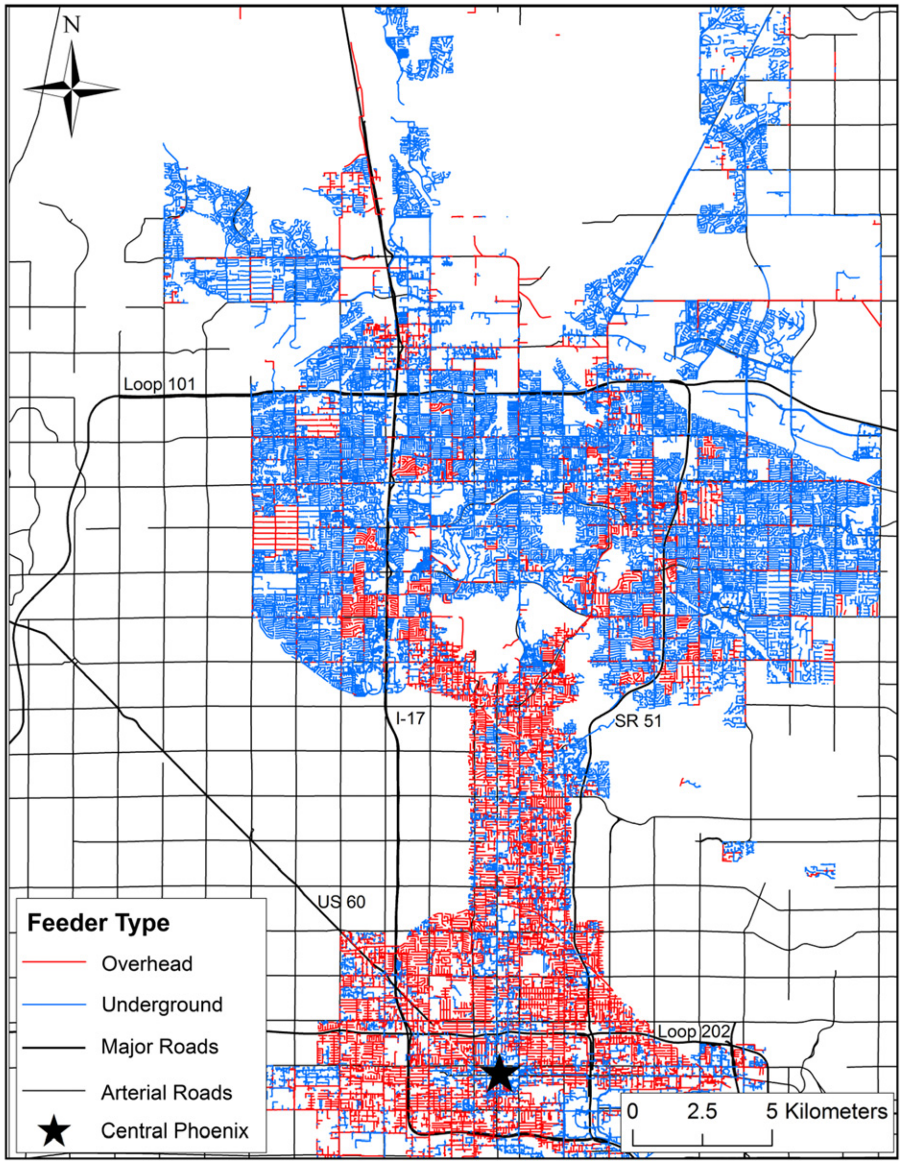

Fig. 2. Map of feeder types.

that home construction sites and other associated groundwork activities may cause underground cable outages through backhoe digging accidents.

3.3. Data

The purpose of reliability modeling is to understand and predict which customers will experience power interruptions given a range of environmental conditions [56]. Interruptions may occur when there is an outage in any part of the power infrastructure system (including the generation, transmission, sub-transmission, and distribution systems). We consider all reported unscheduled power outages in the distribution system since each unscheduled outage is assumed to be an inconvenient interruption to electricity consumers.

There are a large number of environmental factors that potentially cause unscheduled residential power interruptions in Phoenix, but these vary depending on whether electricity is distributed through overhead or underground lines. To examine the factors affecting residential power reliability, data on power line location and type (overhead or underground) were obtained from APS. Fig. 2 is a map showing the feeder line types and locations. APS also provided data on power outages (cause, duration, number of customers affected) for the period 2002–2005, by feeder identification. The reliability data consist of information on outages by proximate cause sourced from the APS outage identification system. We grouped the causes of outages into the following categories: scheduled outages, accidental outages, and environmental outages (a subset of accidental outages). Since we are interested in environmental interactions, we focus on the subset of environmental outages. Since we are interested in residential power reliability, the unit of observation in this study is the single-family housing unit. We gathered housing sale location data from the Maricopa County Assessor's Office (MCAO) and identified the number of outages per house sale location by feeder type. Each housing sale was assigned to its nearest feeder line to account for the number of outages at each sale location. We used housing sale locations in 2005 to account for the location of environmental conditions in the observed outage period. Fig. 3 shows the distribution of environmental outages across the study area.

We further characterized power lines by proximity to other built infrastructures (i.e. arterial roads), measured in Euclidean

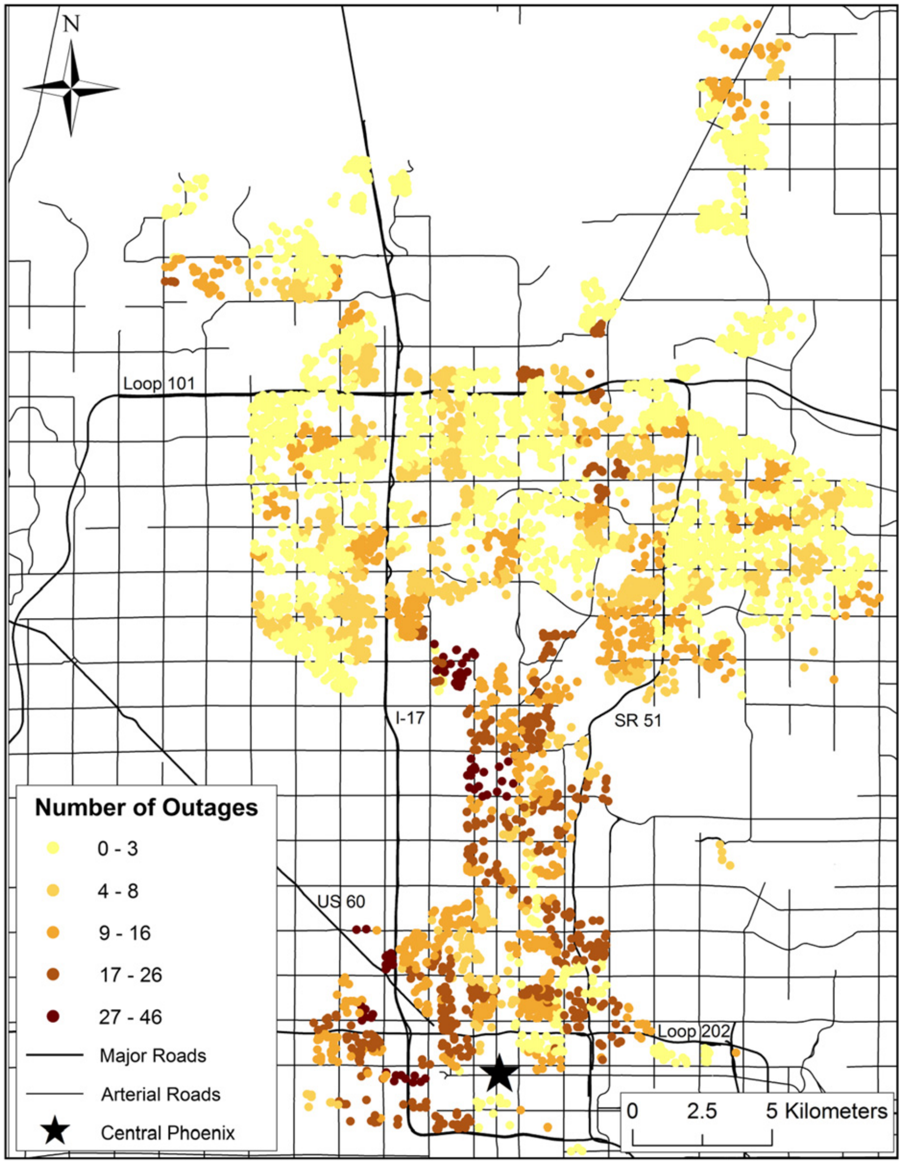

Fig. 3. Map of environmental outages (2002–2005) per house sale in 2005. Graduated symbols classified in natural breaks.

(straight line) distances in meters from the centroid (geometric center) of each parcel to the nearest arterial road. We used the MCAO database of parcels to determine the construction year for each house to serve as a proxy for infrastructure age. Since power outages are reported by feeder, outages were assigned to each house in our sample by its corresponding feeder. This yielded 6061 housing observations.

To create a proxy for energy demand, we used housing characteristics. Data on housing characteristics in 2005 were obtained via the MCAO including house price, house size, lot size, and construction year. Environmental variables relevant to Phoenix residents include vegetation and bird abundance, ambient temperatures, air pollution, and several other metrics to represent proximity to environmental features. The Soil Adjusted Vegetation Index (SAVI) from a Landsat Thematic Mapper (ETM) image was used as a proxy for vegetation abundance. Fig. 4 shows the distribution of vegetation across the study area. Bird abundance was obtained through Central Arizona-Phoenix Long-Term Ecological Research (CAP-LTER) project. Birds were monitored seasonally across 40 sites from 2002 to 2004 and counts were interpolated over the span of the metropolitan area (see [57] for details on the methodology). Fig. 5 shows the estimated distribution of birds across the study area. Temperature data represented by August minimum degrees in Celsius were obtained through CAP-LTER. August minimum temperature was used as a proxy for Phoenix's urban heat island (UHI), and more generally ambient temperature. In the Phoenix metropolitan area, the UHI effect is observed in the elevation of night-time temperatures and is most strongly observed in the summer months [58], thus mean August minima are appropriate indicators. These data were derived from spatial interpolation of daily temperature data from 55 meteorological sensors from different sources including the Flood Control District of Maricopa County (ALERT), the National Weather Service (NWS), the Arizona Meteorological Network (AZMET), and the Phoenix Real-time Instrumentation for Surface Meteorological Studies (PRISMS) Network. Daily measurements were aggregated to bi-weekly periods. GIS data on air pollution were also obtained from CAP LTER, which digitized a contour map created by the Arizona Department of Environmental Quality. This map modeled particulate matter $\leq 10\,\mu m$ (PM_{10}) concentrations ($\mu g\, m^{-3}$) for the region based on samples collected in 2000. The proximity metrics represent the spatial separations between the centroid of sold parcels and the centroid of features of

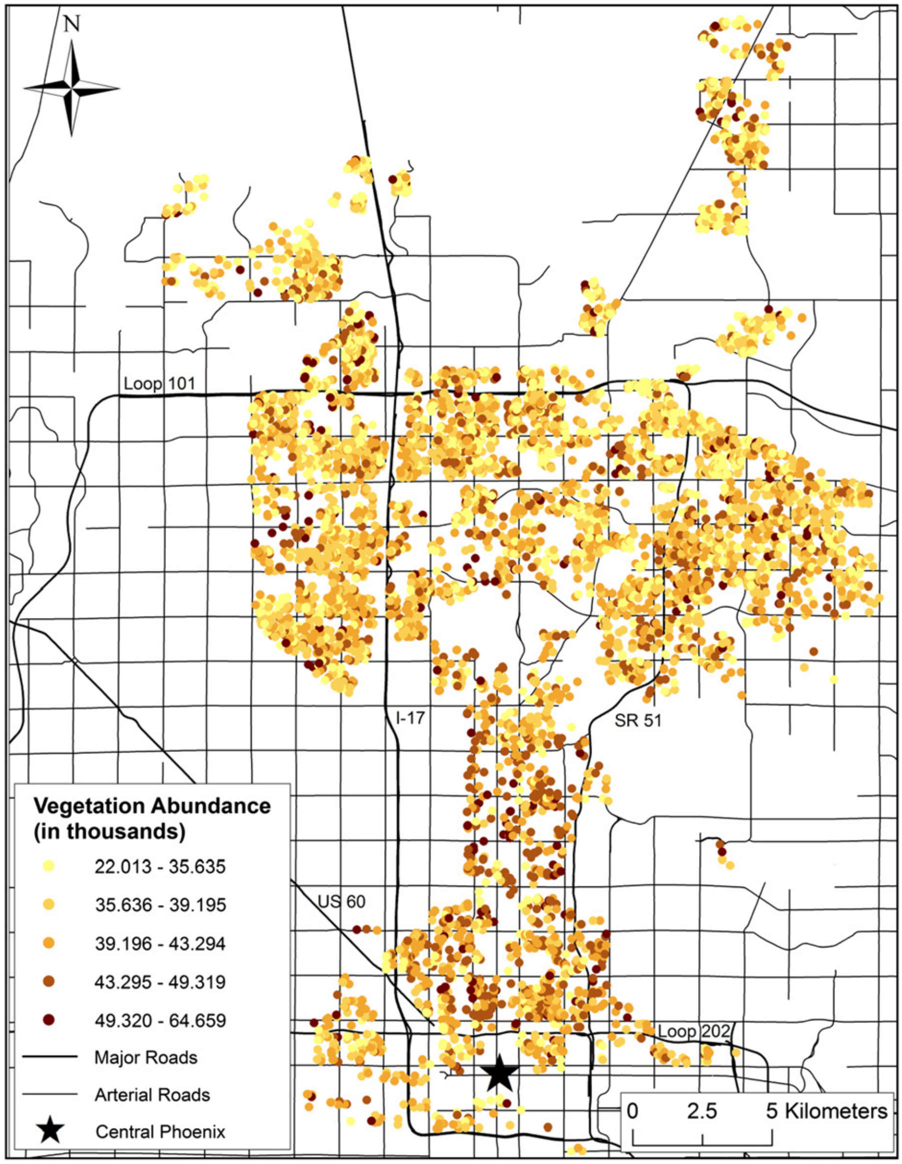

Fig. 4. Map of vegetation abundance (in thousands) per house sale in 2005. Colored symbols classified in natural breaks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interest and were calculated through ArcGIS using Euclidean distances in meters. The proximity metrics examined include proximity to the nearest native desert area, proximity to the nearest small park (<100 ha), proximity to the nearest large park (>100 ha), proximity to the nearest stream, proximity to the nearest lake (excluding the Salt River), proximity to the nearest canal, and proximity to the center city (downtown). The Salt River is excluded from the analysis because a dam in Tempe precludes most flow across Phoenix. Hence, the portion of the Salt River in the city of Phoenix is typically dry. Additionally, the Salt River in the Phoenix is associated more with industry than with residential areas. Variable names, descriptions, and statistics are provided in Table 1.

3.4. Model

There were two main steps to identify the selection of variables for the model. First, we needed to identify the relevant factors that affect the reliability of distribution systems, which were described in detail in Section 2. Second, we needed to identify which of those factors were relevant for the distribution system in Phoenix, which were discussed in Section 3.2. Unscheduled outages are hypothesized to depend on a set of non-environmental and environmental factors: non-environmental factors including infrastructure type and location; environmental factors including temperature, vegetation, bird abundance, and proximity to desert. We estimated a model of the following general functional form:

$$y_i = f(w_i, \mathbf{x}_i, \mathbf{z}_i) + \mathbf{e}, \tag{1}$$

where y_i is the number of environmental outages experienced at location i, w_i is the size of the property at that location (a proxy for energy demand), $\mathbf{x}_i$ is a vector of associated infrastructural conditions, $\mathbf{z}_i$ is a vector of associated environmental conditions, and $\mathbf{e}$ is a vector of error terms.

The general structure of the model is applicable not just to Phoenix, Arizona but to other urban areas. However, the specific components of the vectors $\mathbf{x}_i$ and $\mathbf{z}_i$ would be expected to reflect the characteristics of the area. For Phoenix, the infrastructural conditions comprise the type of infrastructure, and its location with respect to other major built infrastructures such as arterial

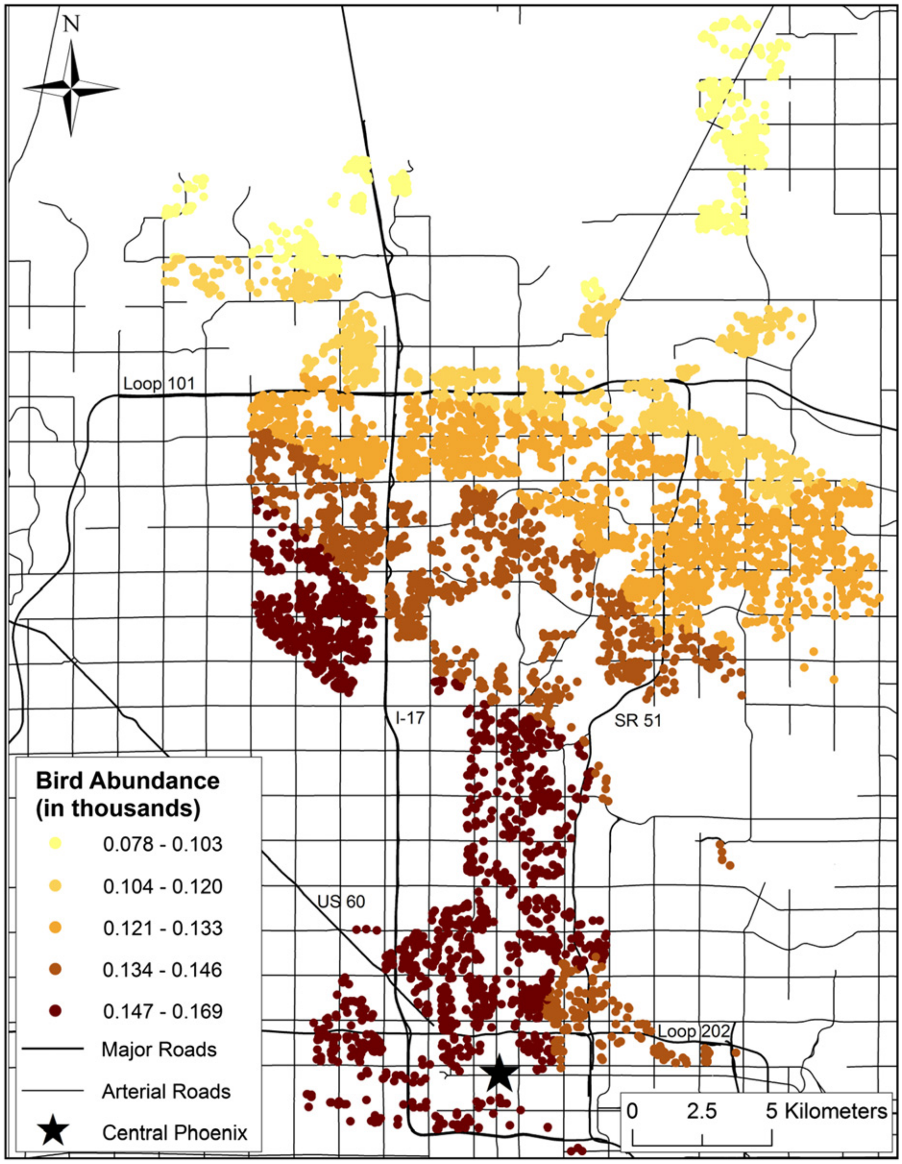

Fig. 5. Map of bird abundance (in thousands) per house sale in 2005. Colored symbols classified in natural breaks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Names, descriptions, and basic statistics of variables ($n=6061$).

Name	Description	Mean	SD	Min	Max
OUT	Number of environmental outages	6.32	7.24	0	46
OH	% Houses in tract supplied by overhead feeder	0.26	0.36	0	1
SQFT	Housing area (sq. km)	0.513	0.177	0.136	1.634
ART	Distance to nearest arterial road (km)	0.314	0.237	0.0002	2.110
VEG	Vegetation abundance; Soil-Adjusted Vegetation Index (in thousands)	39.297	4.765	22.013	64.659
BIRD	Bird abundance (in thousands)	0.130	0.018	0.078	0.169
DES	Distance to nearest desert area (km)	1.746	1.333	0.011	6.301
AGE	Age of house (yrs)	27.80	18.84	1	105
SMPK	Distance to nearest small park (< 100 ha; km)	1.020	0.603	0.001	4.039
LGPK	Distance to nearest large park (> 100 ha; km)	4.778	2.956	0.653	15.624
STRM	Distance to nearest stream (km)	1.040	0.841	0	4.056
LAKE	Distance to nearest lake (km)	1.575	0.926	0.058	5.981
PHX	Distance to center city (km)	20.121	8.024	0.581	38.162
CAN	Distance to nearest canal (km)	3.510	2.377	0	12.475
TEMP	August minimum temperature (Celsius)	21	0.14	20	22
*PM*10	Particulate matter $\leq 10\ \mu m$, concentration ($\mu g\ m^{-3}$)	60.17	16.46	30	110

roads. That is:

$$\mathbf{x} = (\text{feeder type}, \text{proximity to arterial road}). \tag{2}$$

Because infrastructure age is highly correlated with infrastructure type and location, giving rise to problems of multicollinearity, we excluded infrastructure age from the set of explanatory variables. The environmental conditions are measures of species abundance, climatic conditions and distance from the desert. That is

$$\mathbf{z} = (\text{vegetation abundance, bird abundance, proximity to desert, proximity to lake}). \tag{3}$$

The estimated model is

$$y_i = a + \beta_w w_i + \sum_j \beta_j x_{ij} + \sum_j \beta_j z_{ij} + \varepsilon, \tag{4}$$

where

$$\sum_j \beta_j x_j = \beta_{OH} OH + \beta_{ART} ART \tag{5}$$

and

$$\sum_j \beta_j z_j = \beta_{BIRD} BIRD + \beta_{VEG} VEG + \beta_{DES} DES + \beta_{LAKE} LAKE \tag{6}$$

in which each of the variables are described in Table 1.

Interactions between the environmental variables and the type and/or age of infrastructure are captured in a separate set of interaction terms, the expected effects of which depend on the variables concerned. For example, if vegetation or bird abundance interacts with overhead lines we would expect interaction terms between those variables to be positive. The interaction between vegetation, birds, and overhead lines involves the notion that vegetation, especially tall trees, will attract birds because birds are attracted to large trees to provide shelter. Birds interfere with overhead distribution equipment directly, and potentially move branches that may interfere with overhead lines. Further, areas with abundant vegetation and birds may also attract other wildlife that can interfere with overhead distribution equipment. We expect such areas to experience more outages than areas with underground cables, fewer trees, and fewer birds. We also expect an interaction between energy demand (proxied by housing square footage) and temperature since extreme heat events will induce higher levels of energy demand in larger houses than in smaller houses. We accordingly also estimated an interaction model of the form:

$$y_i = a + \sum_j \beta_j z_{ij} w_i + \sum_j \beta_j x_{ij} + \sum_j \beta_j z_{ij} + \sum_j \beta_j x_{ij} z_{ij} + \varepsilon, \tag{7}$$

where

$$\sum_j \beta_j z_{ij} w_i = \beta_{SQFT\,TEMP}(SQFT\,TEMP) \tag{8}$$

and

$$\sum_j \beta_j x_{ij} z_{ij} = \beta_{BVOH}(BIRD\,VEG\,OH) + \beta_{DESOH}(DES\,OH) + \beta_{LAKEOH}(LAKE^{*}OH). \tag{9}$$

Several estimation methods were used. Initially we used ordinary least squares (OLS). Since we used count data, and the distribution of outages is positively skewed, we also estimated the model using generalized linear regression, including both Poisson's, zero inflated Poisson and negative binomial regression, using pseudo-R^2 values based on the residual deviance over the null deviance to measure goodness of fit for each method (see [59,60]).

An important issue to be addressed in the estimation of this model is the likelihood that an interruption at one house is dependent on an outage at a nearby feeder. The result of this is a highly spatially correlated set of observed outages where houses in a neighborhood supplied by the same feeder will likely experience the same interruption. This would generally be the case where power distribution systems rely on a radial system of energy distribution [26,61], but can still occur with loop systems. Radial distributions provide energy to customers directly from a transformer to nearby end users whereas looped distribution systems are interconnected, allowing for back-end power supply routes in case a component fails. The negative outcome of a radial distribution fault is that any home downstream of a failure in a radial distribution will experience an interruption. Although the distribution system is likely to have both looped and radial feeders, we do not have data to indicate this. Nor do we have data on distribution substation locations that could be used to identify network topologies.

Table 2
Environmental outage results ($n = 6061$).

Name	Relative importance	Coefficient	t
Constant	–	−0.285	−0.313
SQFT TEMP	0.017	0.160	7.742
OH	0.409	11.676	28.727
ART	0.005	−1.058	−3.510
BIRD	0.124	13.624	2.564
VEG	–	0.004	0.240
BIRD VEG OH	0.247	1.252	16.688
DES OH	0.102	−1.258	−14.145
*LAKE*OH*	0.097	−2.529	−12.002
Adj. R^2	–	0.431	–
AIC	–	37,789	–
Jarque–Bera	–	4180.211	$p < 0.001$
MCN	–	37.517	–

Note: MCN: multicollinearity condition number; relative importance (LMG) metrics may not add up to one due to rounding.

To account for spatial autocorrelation and abate spatial interdependency issues, we controlled for spatial effects [62,63]. Spatial dependence can take two forms. First, spatial dependence can result from underlying spatial interaction processes in the form of externalities. Second, spatial dependence can result from misspecification in the form of omitted variables, incorrect functional specification, or measurement error. In reality, houses are dependent on the reliability of the feeder rather than a neighboring house; however, since we assign houses to its closest feeder, we can assume therefore that houses are dependent on each other's reliability. Furthermore, neighborhoods containing many houses will have similar biophysical environments suggesting houses exposed to environmental conditions such as birds, vegetation, overhead lines, or desert conditions will experience a similar effect. Consequently, we ran spatial diagnostic tests to determine whether spatial error dependence should be controlled for in the model before coefficient estimation. The spatial diagnostic tests were based on a Moran's I analysis of the OLS residuals and Lagrange Multiplier methods detailed in Anselin et al. [64] using a binary spatial weights matrix with neighbors defined on the basis of a distance threshold. We constructed a spatial error model to incorporate and assess the effect of spatial dependence in the form of spatial measurement error formally expressed as

$$y = X\beta + u \tag{10}$$

in which $u = \lambda Wu + \varepsilon$ is a vector of spatially autocorrelated error terms, W is a row-standardized spatial weights matrix and λ is the spatial error coefficient to be estimated. The incorporation of spatial dependence through spatial weighting in the spatial error model includes a spatially lagged vector of error terms that is effectively treated as noise. We estimated the model using maximum likelihood methods in GeoDa™ [65].

4. Results

Coefficient estimates for the environmental outage model estimated with OLS are reported in Table 2. The overall OLS fit is reasonable (adjusted $R^2=0.431$). Diagnostics reveal moderate multicollinearity (Multicollinearity Condition Number=37.517), but do not indicate that the estimates are biased (Multicollinearity Condition Number < 100). Table 2 reports measures of the relative importance of each of the outage factors. Relative importance in this case is based on the LMG metric which, when normalized, gives the percentage explanatory power of each of elements in the R^2 value [66,67]. We used the LMG metric because it provides an effective way of prioritizing intervention options, and because its calculation is straightforward [68].

The interaction between size of dwellings and August minimum temperature, our proxy for heat-related energy demand, has a positive and significant impact on outages. However, the main factor associated with outages is the vulnerability of the infrastructure. The coefficient for overhead power lines, measured as the percentage of overhead power lines in the census tract of each parcel, is positive and highly significant. Proximity to the nearest arterial road, a proxy for exposure to traffic and congestion, has a positive and significant influence on outages.

Of the environmental variables, the effect of the interaction between bird abundance, vegetation abundance, and overhead lines provides is strongly positive and highly significant, representing the second most important factor in determining outages across Phoenix. After controlling for this interaction, bird quantity on outages is still positive and significant. Distance from the natural desert area is negative and also highly significant. The effect of vegetation abundance is also positive, but is not significant at the 5% level, indicating the presence of vegetation is less important than the interaction between vegetation and other environmental and infrastructural conditions. In other words, vegetation is insignificant because we control for the interaction between vegetation and overhead lines. Without that interaction, vegetation is significant but weak because it ignores the interaction effect and it does not appropriately represent the impact of vegetation on the distribution system. The variable was accordingly excluded from the calculation of relative importance of each variable.

Since the dependent variable is represented by counts of unscheduled outages, it could be argued that using an OLS estimator is inappropriate given the highly skewed nature of count data. We accordingly re-estimated the model using generalized linear regression (i.e., Poisson's regression, negative binomial regression, and a zero inflated Poisson's regression). Results are reported in Table 3. A comparison of pseudo-R^2 values (based on the observed deviance over the null deviance) and AIC criteria indicated the OLS estimations provide a better fit than the Poisson and zero-inflated Poisson regressions. However, the AIC criteria indicated the negative binomial regression performed better than the OLS estimation [69]. An analysis of the distribution of each model's residuals via the Jarque–Bera test for normality indicated that the residuals were significantly non-normal [70]. Although the unscheduled outage counts in this paper were positively skewed, the residuals from the OLS estimation were not as skewed as the resulting residuals from zero inflated Poisson's regression. The interpretation of the model remained similar for each of the generalized linear regressions except for vegetation abundance, which became positive and significant in the zero inflated Poisson's regression.

Results for the spatial error models are reported in Table 4. Distance matrices were based on distance thresholds such that observations within 250 m, 300 m, and 350 m of each observation were considered neighbors. The resulting fit of the model improves substantially with the incorporation of the spatial component. Both the pseudo-R^2 values and AIC criteria are noticeably better for the spatial error models than both the OLS and generalized linear regressions. The interpretation of the spatial model in comparison with the original model remains similar, except for the interaction between overhead lines and proximity to the nearest desert. In particular, the interaction becomes insignificant when the neighbor threshold exceeds 300 m.

5. Discussion

The vulnerability of the power distribution system in central Phoenix to environmental factors is strongly related to whether

Table 4
Spatial model results ($n=6061$).

Name	250 m		300 m		350 m	
	Coef.	*z*	Coef.	*z*	Coef.	*z*
Constant	−3.815	−2.766	−6.613	−4.225	−1.266	−0.731
SQFT TEMP	0.033	2.159	0.032	2.157	0.020	1.405
OH	8.059	16.100	6.430	11.485	6.592	10.876
ART	−1.859	−4.504	−1.384	−3.461	−1.183	−3.193
BIRD	66.60	6.314	90.580	7.516	51.260	3.799
VEG	0.007	0.422	0.011	1.280	−0.003	−0.351
BIRD VEG OH	0.443	6.985	0.262	4.080	0.285	4.545
DES OH	−0.237	−2.404	−0.085	−0.816	−0.035	−0.335
LAKE OH	−0.893	−4.704	−0.572	−2.933	−0.600	−3.143
λ	0.801	134.442	0.841	150.648	0.863	153.601
Pseudo-R^2	0.831	–	0.841	–	0.848	–
AIC	32,091	–	31,651	–	30,972	–

Table 3
Generalized linear model results ($n=6061$).

Name	Poisson		Zero-inflated Poisson		Negative binomial	
	Coef.	*z*	Coef.	*z*	Coef.	*z*
Constant	0.243	3.173	1.094	14.071	0.407	2.50
SQFT TEMP	0.028	18.069	0.013	8.494	0.033	9.044
OH	1.430	52.193	1.449	52.195	1.519	21.580
ART	−0.186	−7.559	−0.243	−9.892	−0.317	−5.717
BIRD	5.300	11.047	0.939	1.909	3.144	3.218
VEG	0.002	1.524	0.004	3.131	0.003	1.1167
BIRD VEG OH	0.098	23.181	0.041	9.298	0.091	7.207
DES OH	−0.106	−22.617	−0.067	−14.254	−0.097	−6.561
LAKE OH	−0.184	−15.161	−0.033	−2.508	−0.140	−3.912
Pseudo-R^2	0.290	–	–	–	0.065	–
AIC	43,916	–	38,851	–	33,000	–
Jarque–Bera	317.546	$p<0.001$	6852.211	$p<0.001$	20.289	$p<0.001$

the lines are overhead or underground. It is not at all surprising that overhead distribution lines are more vulnerable to environmental shocks than concealed distribution cables, given their greater exposure to weather events, to vegetation, and to animals (i.e. especially birds). The exposure effect is exacerbated by the fact that overhead lines in Phoenix tend to be older, and have depreciated more than underground cables. Because overhead power lines are also older than underground power cables, their vulnerability is a function of both exposure and age. We found, for example, that the vulnerability of power lines decreases with increasing distance from arterial roads. While this reflects the impact of traffic and congestion, it also reflects on the age of the infrastructure, since the infrastructure near arterial routes is typically older than the infrastructure farther away from those routes.

What may be more surprising in the Phoenix data is the significance of two environmental effects: the interaction between overhead lines and distance to the desert (negative and significant) and the interaction between overhead power lines, vegetation and birds. Distance to desert is a proxy for the impact of sand or dust. Proximity to desert implies increased exposure to dust and sand saltation from desert areas. Since storms are infrequent events, this may indicate that wind-borne sand is a significantly greater environmental threat to overhead distribution lines than the wind-borne snow or rain that accounts for a majority of environmental outages in the East. Further, sand and dust may build up on insulators eventually leading to flashovers. The interaction between overhead power lines, vegetation and birds is a measure of the interaction between these environmental variables and the infrastructure. Interactions between trees and power lines are amplified by the effect of birds. The mechanisms may be different in both cases, but the same vegetation conditions that threaten power lines in windy periods also support high bird abundances. Birds may directly interrupt electricity supply through the effects on overhead distribution lines described earlier, but may also attract predators such as cats that interfere with overhead distribution lines. Although trees are widely distributed in the study area (see Fig. 4), it is the interaction between trees, birds and overhead lines that is significant. It is possible that this correlates with flood irrigated areas, since these are known to have strong, positive effects on both vegetation biomass and bird abundance. We have not, however, tested the indirect consequence of flood-irrigated areas.

The strongest and perhaps most obvious finding is that the number of outages at one location strongly depends on the number of outages at neighboring locations (i.e., up to around 350 m). This is because neighboring houses are likely to have similar biophysical conditions, have similar heat–energy demand related characteristics, and be served by the same feeder that experiences an outage. One limitation of this study is the potential bias resulting from the omission of a term representing the interconnection of feeder lines. We do not have information on whether feeders are looped or radial in design, nor do we have information on distribution substation locations to derive network topologies. Hence, we were not able to incorporate an interconnection component in the model.

6. Conclusion

While our findings build on existing studies on understanding the factors determining residential electrical distribution reliability, we have adopted an approach that is different from those found in the existing literature. We have explored some of the interacting factors that help to understand the reliability of the electricity distribution infrastructure in Phoenix, Arizona. Better understanding of the interactions between infrastructure type and the biophysical environment can help improve environmental planning for electrical distribution reliability. Underground cables are safer, more esthetically pleasing, and more reliable than overhead lines [71]. Since overhead line installation and repair is significantly cheaper than underground line installation and repair [72], there is perhaps a short-term attraction to overhead lines. However, since overhead lines are also more vulnerable, particularly in interaction with other elements of the urban environment, it is not as clear that their use is efficient in the long run. As such, the efficiency of underground versus overhead lines is yet to be determined. In follow-up research we are considering the extent to which the reliability of power infrastructures is capitalized into the value of housing, and hence identifying its value to consumers. Regardless of the value estimates revealed by that exercise, understanding the physical interaction between infrastructures and environmental factors can inform strategies for managing those infrastructures.

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References

[1] Chang SE, McDaniels TL, Mikawoz J, Peterson K. Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 ice storm. Natural Hazards 2007;41:337–58.
[2] Kariuki KK, Allan RN. Assessment of customer outage costs due to electric service interruptions: residential sector. IEE Proceedings—C 1996;143(2):163–70.
[3] LaCommare KH, Eto JH. Cost of power interruptions to electricity customers in the United States (US). Energy 2006;31:1845–55.
[4] Hines P, Apt J, Talukdar J. Large blackouts in North America: historical trends and policy implications. Energy Policy 2009;37:5249–59.
[5] Albert R, Albert I, Nakarado GL. Structural vulnerability of the North American power grid. Physical Review E 2004;69(2). 025103-1-4.
[6] Latora V, Marchiori M. Vulnerability and protection of infrastructure networks. Physical Review E 2005;71(1). 015103-1-4.
[7] Pahwa A. Effect of environmental factors on failure rate of overhead distribution feeders. 2004 IEEE Power Engineering Society General Meeting 2004:691–2.
[8] Zhou Y, Pahwa A, Yang SS. Modeling weather-related failures of overhead distribution lines. IEEE Transactions on Power Systems 2006;21(4):1683–90.
[9] Maliszewski PJ, Perrings C. Factors in the resilience of electrical power distribution infrastructures. Applied Geography 2012;32(2):668–79.
[10] Hamilton JC, Johnson RJ, Case RM, Riley MW. Assessment of squirrel-caused power outages. In: Fagerstone KA, Curnow RD, editors. Vertebrate pest control and management materials: vol 6, ASTP STP 1055. Philadelphia: American Society for Testing Materials; 1989. p. 34–40.
[11] Bevanger K. Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. Ibis 1994;36:412–25.
[12] Ang AHS, Pires JA, Villaverde R. A model for the seismic reliability assessment of electric power transmission systems. Reliability Engineering and System Safety 1996;51:7–22.
[13] Simpson P, Van Bossuyt R. Tree-caused electric outages. Journal of Arboriculture 1996;22:117–21.
[14] Fritts TH. Economic costs of electrical system instability and power outages caused by snakes on the island of Guam. International Biodeterioration Biodegradation 2002;49:93–100.
[15] Hamza ASHA, Abdelgawad NMK, Arafa BA. Effect of desert environmental conditions on the flashover voltage of insulators. Energy Conversion and Management 2002;43:2437–42.
[16] Balijepalli N, Venkata SS, Richter CW, Christie RD, Longo VJ. Distribution system reliability assessment due to lightning storms. IEEE Transactions on Power Delivery 2005;20:2153–9.

[17] Adachi T, Ellingwood BR. Serviceability of earthquake-damaged water systems: effects of electrical power availability and power backup systems on system vulnerability. Reliability Engineering and System Safety 2008;93:78–88.
[18] Han SR, Guikema SD, Quiring SM, Lee KH, Rosowsky D, Davidson RA. Estimating the spatial distribution of power outages during hurricanes in the Gulf coast region. Reliability Engineering and System Safety 2009;94:199–210.
[19] Oral B, Donmez F. Analysis of the power blackout in the Marmara earthquake. Elektron Elektrotech 2010;8:77–80.
[20] Brown RE. Electric power distribution reliability. New York: Marcel Dekker; 2002.
[21] IEEE. IEEE Standard 1159–1995, Recommended practice for monitoring power quality. New York: IEEE; 1995.
[22] Pyy P. An analysis of maintenance failures at a nuclear power plant. Reliability Engineering and System Safety 2001;72:293–302.
[23] Heo G, Park J. A framework for evaluating the effects of maintenance-related human errors in nuclear power plants. Reliability Engineering and System Safety 2010;95:797–805.
[24] Billinton R. Power system reliability evaluation. New York: Gordon and Breach; 1970.
[25] Bollen MHJ. Understanding power quality problems. Piscataway, NJ: IEEE; 2000.
[26] Willis HL, Welch GV, Schrieber R. Aging power delivery infrastructures. New York: Marcel Dekker; 2001.
[27] De la Ree J, Liu Y, Mili L, Phadke AG, DaSilva L. Catastrophic failures in power systems: causes, analyses, and countermeasures. Proceedings of IEEE 2005;93:956–64.
[28] Arya LD, Choube SC, Arya R. Probabalistic reliability indices evaluation of electrical distribution system accounting outage due to overloading and repair time omission. International Journal of Electrical Power 2011;33:296–302.
[29] He J, Sun Y, Wang P, Cheng L. A hybrid conditions-dependent outage model of a transformer in reliability evaluation. IEEE Transactions on Power Delivery 2009;24(4):2025–33.
[30] Liu H, Davidson RA, Apanasovich TV. Spatial generalized linear mixed models of electrical power outages due to hurricanes and ice storms. Reliability Engineering and System Safety 2008;93:897–912.
[31] Winkler J, Dueñas-Osorio L, Stein R, Subramanian D. Performance assessment of topologically diverse power systems subjected to hurricane events. Reliability Engineering and System Safety 2010;95:323–36.
[32] Kwasinski A, Weaver WW, Chapman PL, Krein PT. Telecommunications power plant damage assessment for hurricane Katrina: Site survey and follow-up results. IEEE Systems Journal 2009;3(3):277–87.
[33] Hoffmann JM, Hoffmann DJ, Kroll EC, Wallace JW, Kroll MJ. Electrical power cord damage from radiant heat and fire exposure. Fire Technology 2001;37:129–41.
[34] Smoyer-Tomic K, Kuhn R, Hudson A. Heat wave hazards: an overview of heat wave impacts in Canada. Natural Hazards 2003;28:463–85.
[35] Miyazaki T, Okabe S. Experimental investigation to calculate the lightning outage rate of a distribution system. IEEE Transactions on Power Delivery 2010;25(4):2913–22.
[36] Farzaneh M, Kiernicki J. Flashover performance of ice-covered insulators. Canadian Journal of Electrical Computer Engineering 1997;22:95–109.
[37] Bertling L, Allan R, Eriksson R. A reliability-centered asset maintenance method for assessing the impact of maintenance in power distribution systems. IEEE Transactions on Power System 2005;20:75–82.
[38] Poulos HM, Camp AE. Decision support for mitigating the risk of tree induced transmission line failure in utility rights-of-way. Environmental Management 2010;45:217–26.
[39] Tennessee Valley Authority. Right-of-way vegetation maintenance frequently asked questions. 〈http://www.tva.gov/power/rightofway/faq.htm〉. Last accessed 25.03.11.
[40] Kuntz PA, Christie RD, Venkata SS. Optimal vegetation maintenance scheduling of overhead electric power distribution systems. IEEE Transactions on Power Delivery 2002;17(4):1164–9.
[41] Guikema SD, Davidson RA, Liu H. Statistical models of the effects of tree trimming on power system outages. IEEE Transactions on Power Delivery 2006;21(3):1549–57.
[42] Radmer DT, Kuntz PA, Christie RD, Venkata SS, Fletcher RH. Predicting vegetation-related failure rates for overhead distribution feeders. IEEE Transactions on Power Delivery 2002;17(4):1170–5.
[43] Zhou Y, Pahwa A, Yang S. Modeling weather-related failures of overhead distribution lines. IEEE Transactions on Power Systems 2006;21:1683–90.
[44] Beaty HW. Electric power distribution systems: a non-technical guide. Tulsa, OK: PenWell Publishing Company; 1998.
[45] James JB, Hellgren EC, Masters RE. Landscape correlates of wildlife-related power outages at electrical substations. Wildlife Society Bulletin 2002;30:148–55.
[46] Chow MY, Taylor LS. Analysis and prevention of animal caused faults in power distribution systems. IEEE Transactions on Power Delivery 1995;10(2):995–1001.
[47] IEEE Task Force on Reducing Bird Related Power Outages. Preventive measures to reduce bird-related power outages—part I: Electrocution and collision. IEEE Transactions on Power Delivery 2004;19(4):1843–7.
[48] Harness RE, Wilson KR. Electric-utility structures associated with raptor electrocutions in rural areas. Wildlife Society Bulletin 2001;29:612–23.
[49] U.S. Census Bureau. 2010; 〈www.census.gov〉. Last accessed on 24.03.11.
[50] Carlsson F, Martinsson P. Willingness to pay among Swedish households to avoid power outages: a random parameter tobit model approach. Energy Journal 2007;28:75–89.
[51] Pasqualetti MJ. Wind power: obstacles and opportunities. Environment 2004;46(7):22–38.
[52] National Oceanic and Atmosphere Administration. Climatology of the United States No. 20 1971-2000: Phoenix Sky HRBR INTL AP, AZ. 2004. 〈http://cdo.ncdc.noaa.gov/climatenormals/clim20/az/026481.pdf〉. Last accessed 25.03.11.
[53] The contribution of Eastern North Pacific tropical cyclones to the warm season rainfall climatology of the Southwestern United States; 〈http://www.atmos.albany.edu/student/kristen/monsoon.html〉. Last accessed on 15.03.11.
[54] Arizona earthquake history; 〈http://earthquake.usgs.gov/earthquakes/states/arizona/history.php〉. Last accessed on 15.03.11.
[55] Sima W, Yang Q, Ma GQ, Jiang CL, Wu LA, Cheng H. Experiments and analysis of sand dust flashover of the flat plate model. IEEE Transaction on Dielectrics and Electrical Insulation 2010;17:572–81.
[56] Brown RE, Gupta S, Christie RD, Venkata SS, Fletcher R. Distribution system reliability assessment: Momentary interruptions and storms. IEEE Transactions on Power Delivery 1997;12:1569–75.
[57] Walker JS, Balling RC, Briggs JM, Katti M, Warren PS, Wentz EA. Birds of a feather: interpolating distribution patterns of urban birds. Computers Environment and Urban Systems 2008;32:19–28.
[58] Baker LA, Brazel AJ, Selover N, Martin C, McIntyre N, Steiner FR, Nelson A, Musacchio L. Urbanization and warming of Phoenix (Arizona, USA): impacts, feedbacks and mitigation. Urban Ecosystem 2002;6:183–203.
[59] Liu H, Davidson RA, Rosowsky DV, Stedinger JR. Negative binomial regression of electric power outages in hurricanes. Journal of Infrastructure Systems 2005;11(4):258–67.
[60] Hilbe JM. Negative binomial regression. Cambridge, UK: Cambridge University Press; 2011.
[61] Perrier N, Agard B, Baptiste P, Frayret J, Langevin A, Pellerin R, et al. A survey of models and algorithms for emergency response logistics in electric distribution systems—part 1: reliability planning with fault considerations. Montreal, Canada: Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation, and Department of Mathematics and Industrial Engineering, Ecole Polytechnique de Montreal; 2010.
[62] Anselin L. Spatial econometrics: methods and models. Dordrecht: Kluwer Academic Publishers; 1988.
[63] Anselin L. Spatial externalities, spatial multipliers, and spatial econometrics. International Regional Science Review 2003;26:153–66.
[64] Anselin L, Bera AK, Florax R, Yoon MJ. Simple diagnostic tests for spatial dependence. Regional Science and Urban Economics 1996;26:77–104.
[65] Anselin L, Syabri I, Kho Y. GeoDa: an introduction to spatial data analysis. Geographical Analysis 2006;38:5–22.
[66] Grömping U. Relative importance for linear regression in R: the package relaimpo. Journal of Statistical Software 2006;17(1). Last accessed 24.03.11 〈http://www.jstatsoft.org/v17/i01/〉.
[67] Lindeman RH, Merenda PF, Gold RZ. Introduction to bivariate and multivariate analysis. Glenview, IL: Scott, Foresman; 1980.
[68] Grömping U. Estimators of relative importance in linear regression based on variance decomposition. Am Stat 2007;61:139–47.
[69] Akaike H. A new look at the statistical model identification. IEEE Transactions on Automatic Control 1974;19:716–23.
[70] Jarque CM, Bera AK. A test for normality of observations and regression residuals. International Statistical Review 1987;55:163–72.
[71] Bumby S, Druzhinina E, Feraldi R, Werthmann D, Geyer R, Sahl J. Life cycle assessment of overhead and underground primary power distribution. Environmental and Science Technology 2010;44:5587–93.
[72] Johnson BW. Out of sight, out of mind? A study on the costs and benefits of undergrounding overhead power lines Washington, DC: Edison Electric Institute; 2006.