

THESIS



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Ecology and Control of Wildlife Damage to
Electric Substations

presented by
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A handwritten signature in cursive script that reads "Glen R. Dudderar".

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**ECOLOGY AND CONTROL OF WILDLIFE DAMAGE TO ELECTRIC
SUBSTATIONS**

By

Wendy Hope Sangster

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

Department of Fisheries and Wildlife

1995

ABSTRACT

ECOLOGY AND CONTROL OF WILDLIFE DAMAGE TO ELECTRIC SUBSTATIONS

By

Wendy Hope Sangster

This study addresses several aspects of the ecology and control of wildlife damage to electric substations because the amount of existing research is not sufficient to make informed decisions about how best to minimize that damage. Records of 121 incidents of animal-caused faults showed that 78% of the faults were caused by squirrels and raccoons and an average of 2,511 customers lost service during the outage caused by such a fault. Animal damage control measures were evaluated by observing challenges to control measures by raccoons and squirrels at a substation. The control measures were breached twice because they had not been properly applied.

In 1994, 301 transmission and distribution substations in Michigan were sampled and categorized based on various structural and habitat characteristics. Significant relationships ($p < 0.10$) were found between faulted substations and the number of nests in the substation, the distance of water from the substation, and the beam type used in the substation.

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To my parents Lanny and Wayne Sangster, my sisters Julie and Karin, and Pete, thank you for all of your support throughout my life.

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INTRODUCTION

Although urbanization has adversely affected many wildlife species, other species have not been so affected. The apparent resiliency of some species could be the result of the tolerance of the species to human presence and disturbance, an increase in available suitable habitat because of urbanization, or a combination of both factors. Studies of bird populations have shown that many bird species, such as blue jays (*Cyanocitta cristata*), American robins (*Turdus migratorius*), and European starlings (*Sturnus vulgaris*), are not only able to survive in urban and suburban environments, but in fact thrive in these areas (Williamson 1973, Beissinger & Osborne 1982, Horn 1985). The North American raccoon (*Procyon lotor*), the eastern grey squirrel (*Sciurus carolinensis*), the fox squirrel (*S. niger*), and the red squirrel (*Tamiasciurus hudsonicus*) have all shown similar responses to urbanization (Cauley and Schinner 1973, Hathaway 1973, Schneider 1973, Cauley 1974, Williamson 1983). Regardless of whether the increased availability of suitable habitat or the tolerance of the animal to human presence accounts for the presence of these species in urban areas, their presence has a profound impact on the surroundings and people with which they live.

Animals often use man-made structures for den or nesting sites, foraging sites, or as travel routes, and these activities may cause damage to the structures (Cauley and Schinner 1973). Wildlife intrusions into electric power substations and the subsequent damage to those substations is a problem that has recently received more attention by the electric utility industry. Wildlife damage to

substations comes in the form of outages, direct equipment damage, and safety and health hazards to maintenance personnel (Substation Security Working Group 1993). Wildlife damage is among the major causes of momentary outages to substations (Warren 1992).

Animals cause damage to the substation in various ways. Generally, the animal simultaneously touches two electrified components or an electrified component and a grounded component, the equipment short circuits, and a fault occurs that results in a power outage. Such faults might cause an explosion or fire, leaving little to indicate what caused the damage (Mitchell 1977). Squirrels and raccoons also chew on equipment, and when moisture enters, a fault may occur. Birds nesting in a substation may cause damage to the substation in several ways. Bird droppings are corrosive and may cause equipment damage or may accumulate on insulators, causing flashovers (Paula 1989). Additionally nesting materials could cause faults by falling onto parts of the substation and creating a short. A final potential problem with birds nesting in substations is that foraging raccoons and squirrels may enter the substation to get to eggs and nestlings as these are common elements in the diet of raccoons and squirrels (Schneider 1973, Greenwood 1981).

Wildlife-caused faults which result in power outages are perhaps the most costly of the types of damage. Equipment repair, revenue lost while service is down, and the indirect costs of reduced consumer confidence are some of the expenses associated with power outages (Paula 1990). In a review of impacts of wildlife on telephone and electrical services in Waterloo, Ontario, Mitchell (1977) states that none of the utility companies that he reviewed kept systematic records of wildlife damage and could not attribute costs to the damage but assumed it to be low. However, more recently, Enck (1989) found

that the mean cost of an animal-caused fault in New York for 1987 was \$12,500, and Paula (1990) indicates that some animal-caused outages may cost as much as \$500,000. From figures such as these, it is evident that animals have the potential to do costly damage to substations. Yet, very little research has been conducted to determine the importance of various aspects of that damage.

One aspect of the damage involves determining which types of animals cause damage to substations and in what proportions. In a review of records of animal-caused faults from six utility companies in New York state Enck and Brown (1989) found that of 200 animal-caused faults, 55% were caused by squirrels, 12% by raccoons, and 16% by birds. Rochester Gas and Electric Corporation in Rochester, NY estimated that over a period of four years, 90% of animal-caused faults were caused by raccoons and squirrels (Fiske 1992).

Electric utility companies have used a variety of techniques in an attempt to reduce wildlife damage to substations. Among the techniques are chemical repellents, fence barriers, lights, artificial predators (owls, hawks, snakes, etc.), anti-climbing devices, lineguards, electrical fences, bushing guards, and other structural barriers (Fiske 1990, Substation Security Working Group 1993). Qualitative assessments of the effectiveness of such control measures were provided by a guide compiled by the Institute of Electrical and Electronics Engineers in 1993. The guide was very thorough in its description of control measures but did not give any detailed analysis of the various possible treatments.

A potentially significant aspect of wildlife damage to substations is the structure of the substation itself. Enck (1989) found that the substations that were most susceptible to wildlife damage were those that had been operating for

at least 30 years and those with high physical profiles (latticework and structural components more than 8m above the substation equipment). Other possible characteristics of substation structure that may contribute to wildlife damage include the type of beams and the amount of latticework used in construction. Two beam types commonly used in substations are L-shaped beams (angles) and S-shaped beams (I-beams). It is likely that the beam types are not equally climbable by raccoons and squirrels. Specifically, the L-type beams are associated with a lattice system, and therefore may be more attractive to raccoons and squirrels for climbing than other beam types.

The terrestrial habitat surrounding the substation may be an additional factor that influences the cause and amount of damage by wildlife. Enck (1990) found no correlation between surrounding habitat and the number of faults at a substation. However, the terrestrial habitat variables considered in the study and the way in which they were analyzed may not have fully described the relationship between habitat and wildlife damage. There may be habitat variables that are common to the habitats of all species involved with wildlife damage, and the identification of such variables might help in determining whether broad characteristics of the habitat around the substations influences the amount of wildlife damage to that substation.

Important habitat characteristics for fox and grey squirrels include tree density, basal area, species composition, and shrub crown cover, although the requirements are fairly non-specific (Cauley 1974 , Williamson 1983, Steele and Weigl 1992). Factors such as building cover and the presence of pavement have been found to have a negative influence on squirrel activity (Williamson 1983). Red squirrel habitat requirements are likewise non-specific, but the most important variables include tree density and species composition (Layne 1954,

Baker 1983). Raccoons appear to be most limited by the presence of water, good travel routes, and woods for shelter and food (Cauley and Schinner 1973, Schneider 1973, Cauley 1974). Because the species of birds involved in wildlife damage to substations have not been identified, it is difficult to establish what habitat components might influence damage by birds. However, almost any environment will provide habitat for some species of bird (Williamson 1973, Horn 1985). Because of the broad nature of the habitat requirements among the animals involved with wildlife damage to substations, it is possible that there are habitat parameters that are common to all the species and that are also correlated with wildlife damage. However, this possibility has not been thoroughly explored.

It is evident that the amount of existing research dealing with wildlife damage to electric substations is not sufficient to make informed decisions about how best to minimize that damage. The research presented in this study was requested and funded by Consumers Power because the company was interested in reducing losses due to wildlife damage. Therefore, this research addresses questions about how and why animals damage substations and about the effectiveness of animal damage control measures. Investigation of these questions should lead to better informed decisions about how to control animal damage and consequently to less damage.

OBJECTIVES

The objectives of this study were to determine characteristics of substations and the surrounding environment that are associated with animal damage and to examine the effectiveness of preventative measures. These objectives were accomplished by completing three different investigations.

These investigations were -

- 1) the examination of reports of animal-caused faults provided by Consumers Power.**
- 2) the observation of how effectively the current animal damage control measures used by Consumers Power keep animals out of a substation.**
- 3) the characterization of electric substations based on the relationship between animal-caused faults and structural and habitat characteristics.**

STUDY AREA

The study area encompassed most of the counties in the Lower Peninsula of Michigan (Fig. 1). The specific sites studied were distribution and transmission substations located throughout these counties. Those counties not included were Berrien, Cass, Huron, Lapeer, Macomb, Sanilac, St. Clair, Tuscola, Wayne, and Emmet counties.

The Lower Peninsula of Michigan makes up approximately 70% of the total land area of Michigan and is bounded on the west by Lake Michigan and on the east by Lakes Huron, St. Clair, and Erie. The climate of Michigan is a combination of semi-marine and continental and is altered by lake effects that influence temperature, moisture, and wind direction and velocity. The annual average temperature in the southern half of Michigan (Region I) is approximately 9°C and ranges from about -22 to 19°C. In the northern half of Michigan (Region II) average annual temperature is roughly 7°C with a range of -29 to 17.8°C. Total annual precipitation for the Lower Peninsula is around 800mm (Albert 1986, Eichenlaub 1990).

Elevations in the southern half of Lower Michigan range from 580-1280ft but can get as high as 1725ft in northern lower Michigan. The southern region has areas of clay lake plain, ground moraine, end moraine, and outwash plains, and soil textures are mostly loams to clays with sand soils in certain areas on the lake plain. In the northern region physiographic features include outwash plains, end-moraine ridges, ridges of ice contact material, low elevation

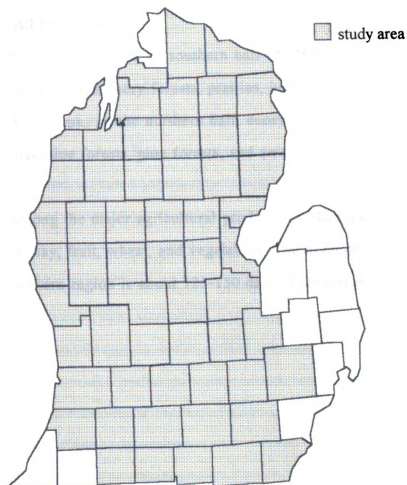


Figure 1. Map of study area

lake plain, ground moraine, and outwash. Sandy soils predominate in this region (Albert 1986).

The ecosystems in the southern half of Michigan include beech-sugar maple forests, oak-hickory forests, prairies, hardwood swamps, and hardwood-tamarack swamps. In the northern half, ecosystems include northern hardwood forests, oak-pine forests, pine forests, and swamp and bog communities (Albert 1986).

Among the major agricultural products of Michigan are milk, corn, soybeans, hay, fruit, wheat, and vegetables. The average growing season length in the southern region is about 125-150 days (Eichenlaub 1990).

METHODS

Examination of Records of Animal-caused Faults

The initial portion of this study involved the examination of data provided by Consumers Power for a period from January, 1988 to September, 1994. The data included information about wildlife damage to substations and were analyzed to establish: 1) which substations had experienced animal-caused faults, 2) what animals caused damage and in what proportions, 3) how the time of day and the time of year of faults were related to the animal causing the fault, 4) what substation equipment was most frequently damaged, 6) how many customers were effected by faults, and 7) how long faults lasted. The results of this analysis provided useful information both for a general description of the problem and for use in the characterization of the substations.

Evaluation of Control Measures

Determining the effectiveness of control measures currently being used by Consumers Power involved the observation of squirrels and raccoons around a substation in Marshall, MI that is used by the company as a training facility. In September and October of 1994 animals were trapped and housed in large outdoor pens at the Dobbie Road Wildlife Research Area at Michigan State University. Animals were trapped in wire box traps. A commercially distributed raccoon bait that consisted of a fish base and anise oil was used to bait raccoons. Squirrels were baited with sunflower seeds, corn, and pecans. Traps were checked at least once a day.

In September of 1994, the substation training facility was prepared for observation of the animals and animal proofed by Consumers Power personnel. A 4-ft high polycarbonate containment fence was erected on the outer side of two sides of the substation about 5ft from the substation fence. The gate into the substation was included in the portion of the facility fenced in. The polycarbonate containment fence had opaque brown paper affixed to one side making it impossible to see through. The two sides of the substation fence within the containment fence were animal proofed. Animal proofing measures included the installation of a 1-inch mesh fence around the substation and the application of 36-inch wide polycarbonate sheeting around the top of the 1-inch mesh fence. Aluminum ties attaching the polycarbonate sheeting to the fence were oriented vertically. The fence and the gate surrounding the substation were to have no openings larger than one inch wide. Gaps at the gate were minimized by applying polycarbonate around the edges of the gate and by sinking the poles of the gate into a concrete base under the gate to maintain proper gate alignment and spacing. The concrete base also prevents the formation under the gate of gaps caused by erosion, use, and animal digging.

On October 6 and 7, 1994 six raccoons were placed within the containment fence and observed and videotaped to determine whether the control measures used by Consumers Power were penetrable. On October 10 and 20, 1994 four melanistic grey squirrels, one fox squirrel, and one red squirrel were likewise placed within the containment fence and then observed and videotaped. Observations of general behavior and if and how an animal gained access to the substation were made. Each animal was observed separately, and observations were made for approximately 2 hours for each

animal or until it escaped. The observations were then tabulated to provide information about the effectiveness of the control measures.

Characterization of Substations

A total of 290 distribution and 11 transmission substations owned by Consumers Power were evaluated and classified from May, 1994 to September, 1994. The 88 substations for which Consumers Power had reported wildlife-caused faults in the last six years were included in the 301 substations; five of the damaged substations were transmission substations and 83 were distribution substations. The remainder of the 301 substations were randomly selected from among the 1,089 substations that had not been damaged by wildlife in the last six years. It was assumed that this sample was representative of the population of substations owned by Consumers Power because the random selection resulted in an interspersed sample and because it made up over a quarter of all of the substations in the population.

One part of the classification of each of the substations included characterizing the structure of the substation. The structural characteristics recorded were beam construction, physical profile, and degree and type of animal proofing. The beam construction for each substation was recorded in terms of beam type, lattice system involved, and the area covered by the structure. Beam types included S-shaped beams (I-beams), L-shaped beams (angles), and wooden poles. To determine whether the amount of latticework associated with L-shaped beams influences damage to substations, substations built with L-shaped beams were classified in two categories: those occupying an area less than 100m^2 and those occupying more than 100m^2 . Therefore, there were five categories of substation structure: substations covering greater than about 100m^2 built with L-shaped beams, substations covering less than 100m^2

built with L-shaped beams, substations built with S-shaped beams, substations built with a combination of L and S-shaped beams, and substations built with wooden poles.

Physical profile was categorized as either high or low. High physical profile was defined as having substation components higher than 7m from the ground, and low physical profile was defined as having all components below 7m. Seven meters was chosen for distinguishing between high and low profile because the high end of low profile substations owned by Consumers Power are typically about 6m tall.

The degree of animal proofing was established by placing the substations into one of three categories. These categories were substations without animal proofing, substations with partial animal proofing, and those with complete animal proofing. Complete animal proofing included: 1) 36 inch wide polycarbonate or aluminum sheeting continuous around the top of the substation fence with plastic or aluminum ties affixed vertically, 2) 36 inch wide polycarbonate or aluminum on all poles outside of the substation within 25m of the substation and/or lineguards placed on all wires going into the substation, 3) no openings of more than 1-inch wide in the fence and gate surrounding the substation or at the gate of the substation, and 4) 1-inch mesh fence around the substation. These are the animal proofing measures that Consumers Power currently uses on its substations. All flaws in animal proofing were noted for each substation.

An additional variable that was considered was the number of bird nests in each substation. The number of nests seen, the location of each nest, and when possible the species of bird associated with the nest were recorded.

The substations were also categorized based on characterizations of the surrounding terrestrial habitat. For each substation visited, terrestrial habitat sampling was conducted in a rectangular plot that included the area within 100m from each side of the substation. Each plot was then divided into four sections based on the four sides of the substation. Each section was stratified by distance from the substation. These stratifications (segments) were: less than 25m from the substation, greater than 25m but less than 50m from the substation, and greater than 50m but less than 100m from the substation (Fig. 2).

First, the vegetative habitat was analyzed within each section and within each distance segment. Species composition and density of woody vegetation within each segment were determined by counting and recording the number and species of trees with a dbh of at least 20cm and by recording the percent crown cover of shrubs less than 5m tall in each segment. Second, man-made structures within each distance segment were evaluated in terms of approximate size, number, and type. Types of man-made structures included fences, cables, houses, and buildings.

Third, the distance of the substation from water and the type of water system were noted. The type of water was recorded as lacustrine or riverine. Categories for the distance of water from a substation were water within 50m or water greater than 50m but less than 150m from the substation.

Finally, the substations were classified based on the spatial arrangement of the vegetative habitat characteristics. Habitat for this classification was defined as areas having at least 120 trees/ha ($3 \text{ trees}/250\text{m}^2$) with a dbh of at least 20cm or areas having at least 50% crown cover of woody vegetation shorter than 5m tall. This definition was considered to be broad enough to

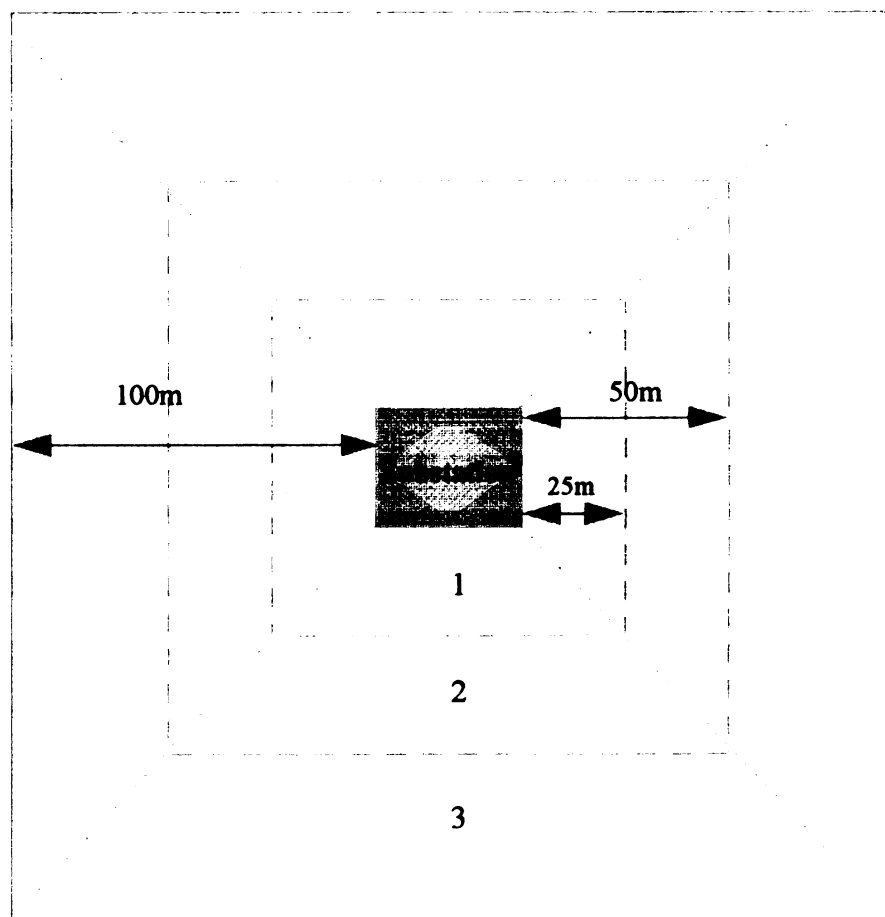


Figure 2. Depiction of habitat sampling design.

provide an indication of adequate habitat for all of the species involved. The spatial arrangements were defined by the following categories: 0 = no habitat (as defined above) within 50m of the substation on any side; 1 = habitat on one side of the substation within 50m of the substation; 2_a = habitat in two adjacent sides of the substation within 50m of the substation; 2_b = habitat on two opposing sides of the substation within 50m; 3 = habitat on three sides of the substation within 50m; 4 = habitat on all four sides of the substation within 50m. It was hypothesized that categories 2_a , 2_b , and 3 would experience more damage than categories 1 and 4 and that category 0 would experience the least amount of damage. Therefore, substations were also classified in each of these three modified categories (0, 14, and 2_a2_b3).

Data Analysis

Data from Consumers Power were analyzed by creating frequency tables of the different variables in the data. This analysis was done to provide a general characterization of animal damage to substations. Specifically, the analysis involved evaluating numbers and types of animals causing faults, times of faults (month and time of day), the types of substation equipment damaged, the average length of faults, and the average number of customers affected by the fault. In the analysis of data obtained from field visits to substations, six distribution substations were not included in any statistical analysis because they were newly built substations and could not have been susceptible to damage by animals during the six years of faults reported by Consumers Power.

Data from the field observations was first analyzed using one-way frequency tables to establish which categorizations would be used in further analysis. Variables in each category with frequencies under 10 were either discarded or combined with another category. Two-way frequency tables were generated for damage versus each classification variables and for variables where association, interaction, or dependence were hypothesized. Chi-square analysis was performed to establish associations for all tables that had a sample size large enough that the test was valid. The Pearson chi-square test was used for this analysis (Altman, D.G. 1991):

$$X^2 = \sum_{i=1}^r \sum_{j=1}^c (O_{ij} - E_{ij})^2 / E_{ij} , \text{ where}$$

O = observed frequencies

E = expected frequencies

r = total number of rows in frequency table

c = total number of columns in frequency table

i = row number

j = column number

For the tables with sample sizes too small to get valid chi-square tests, Fisher's exact test was used. For this test, the hypothesis of homogeneity is rejected when (Freeman, D. H. 1987):

$$2 \min \{P[Y \leq y \text{ (observed)}], P[Y \geq y \text{ (observed)}]\} \leq \alpha, \text{ where} \\ Y \text{ follows a hypergeometric distribution}$$

An association was considered significant for tests with $p < 0.10$. This significance level was used because precision for the field analysis was assumed to be low, as is often the case with field studies. Additionally, the study was largely exploratory, and therefore this significance level was justifiable.

Logistic regression was used to quantify the degree to which combinations of the habitat around substations and the structure of substations influence whether or not the substation is faulted by wildlife. A logistic regression model was developed using animal-caused faults to the substation as the response variable and each of the characteristics involved with the classification of the substations as predictor variables. Data for all but 50 of the categorized substations were used to create the regression model. The 50 substations that had been classified but not used to create the model were then used to determine how well the model classified the substations. The Hosmer and Lemeshow goodness-of-fit test for binary response model, which utilizes the Pearson chi-square analysis, was used to determine the fit of the model. This process established the predictive ability of the logistic regression model. SAS System software was used for all of the statistical analysis (SAS Institute Inc. 1988).

RESULTS

Examination of Records of Animal-caused Faults

Records of animal-caused faults to electric substations between 1988 and 1993 showed that there were 121 incidents of animal-caused faults in 88 of 1,177 transmission and distribution substations. Squirrels accounted for 57%, raccoons for 21%, and birds for 7% of all animal-caused faults (Fig. 3). Forty-two percent of faults caused by squirrels occurred in June, September, and October, with the largest peak occurring in June. Sixty-five percent of faults caused by raccoons occurred in April, May, and August. The number of reports of faults caused by different animals by the month of damage is presented in Figure 4. Faults were most common between the hours of 6:00AM and noon for squirrels and between 9:00PM and 6:00AM for raccoons (Fig. 5). Bird-caused faults occurred in April through September and in December.

Fuses were the most commonly damaged substation equipment; fuses were damaged and replaced in 54% of faulted substations. Other damaged equipment included insulators, arresters, bushings, regulators, transformers, and switches and switchgear (Fig. 6). Outages to customers occurred in 118 of the 121 animal-caused faults. The amount of time that service was off ranged from 15 minutes to 14 hours and 14 minutes, and the average amount of time that service was off was one hour and 46 minutes. The average number of customers that lost service during an outage was 2,511 with a range of 1 to 3,979 people affected per outage.

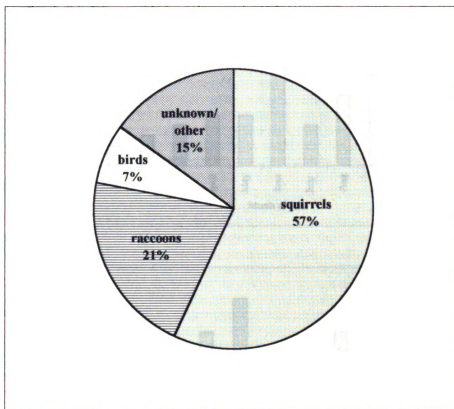


Figure 3. Percentage of reports of animal-caused faults for types of animals responsible for faults.

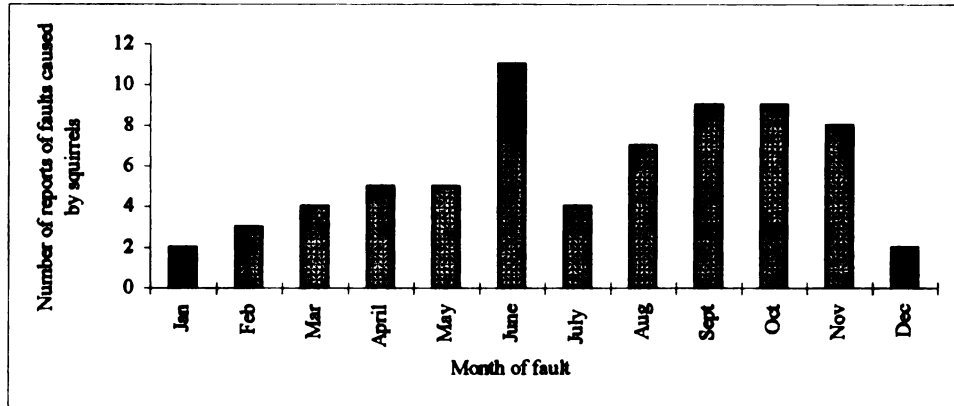
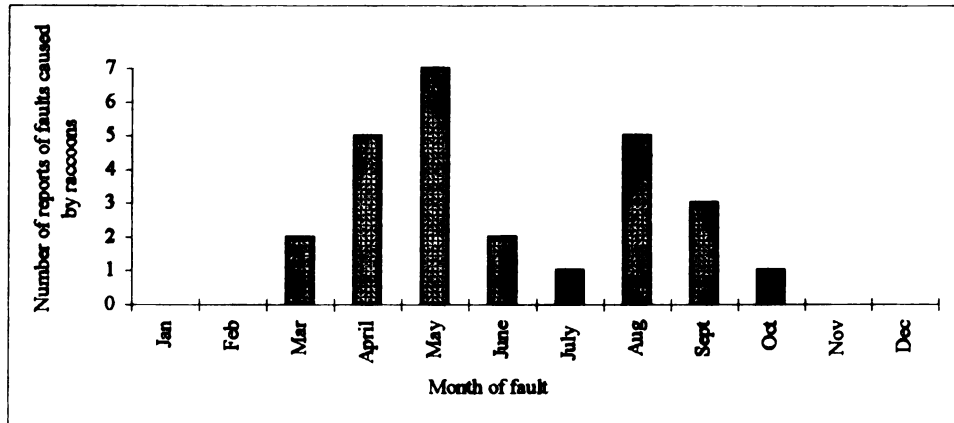
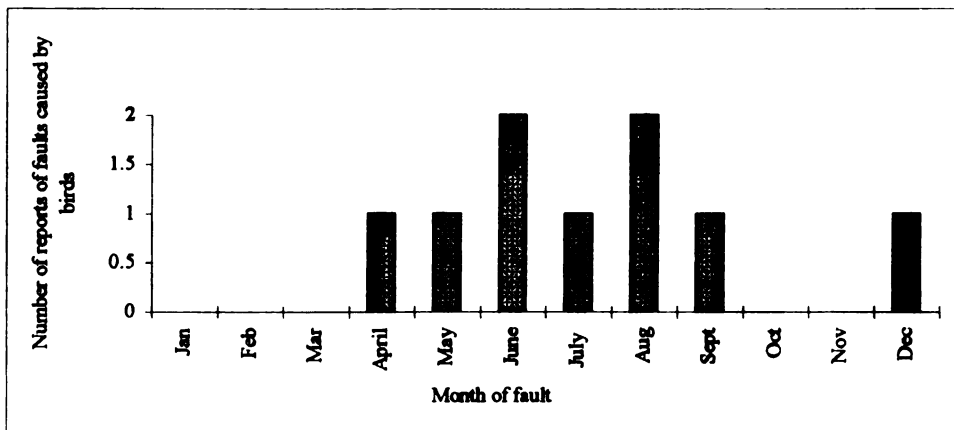
A. squirrels**B. raccoons****C. birds**

Figure 4. Number of reports of animal-caused faults by month for faults caused by squirrels (A), raccoons (B), and birds (C).

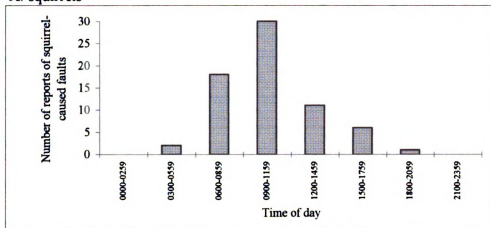
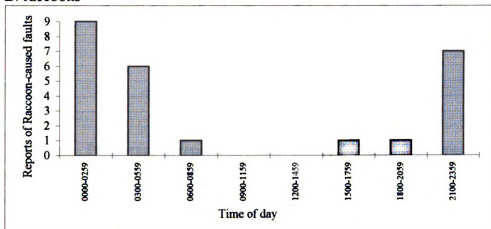
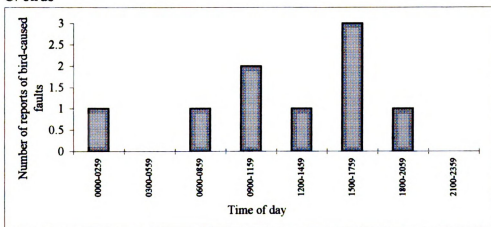
A. squirrels**B. raccoons****C. birds**

Figure 5. Number of reports of animal-caused faults by time of day for squirrels (A), raccoons (B), and birds (C).

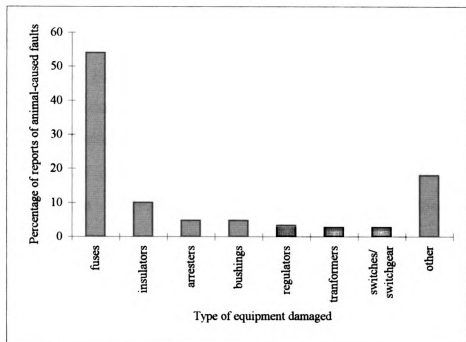


Figure 6. Percentage of reports of animal-caused faults for each type of equipment damaged.

Evaluation of Control Measures

Of the six raccoons and six squirrels observed at the training facility, two raccoons, a red squirrel, and one melanistic grey squirrel escaped from the observation area. However, only one raccoon and the black squirrel escaped through control measures on the substation. The raccoon escaped by pulling the polycarbonate barrier away from the fence where a tie had not been affixed. The black squirrel got into the substation by way of a 1⁵/₈-inch gap between the fence and the gate. Tables 1 and 2 summarize the observations made for each animal.

From the evaluation of 43 animal-proofed substations it was found that common flaws in the application of the control measures included 1) wraps not applied to all poles within 25m of the substation and/or lineguards not applied to all lines going into the substation (81%), 2) ties applied horizontally rather than vertically (81%), 3) polycarbonate sheeting not extended to cover gaps between the substation fence and gate (79%), and 4) gaps larger than 1-inch wide at the gate to the substation (74%). These results are shown in Figure 7. Flaws in animal proofing that were likely to have been the result of insufficient maintenance occurred in 19% of the treated substations.

Table 1. Summary of findings from observations of challenges to control measures by raccoons.

ANIMAL	WEIGHT	SEX	TIME ACTIVE	CHALLENGES TO:			ESCAPE:	
				bottom of fence	upper fence	gate	outer fence	how escaped
raccoon 1	13.75lbs	male	35 minutes	yes	yes	no	no	---
raccoon 2	17.00lbs	female	45 minutes	yes	yes	no	no	---
raccoon 3	30.00lbs	male	15 minutes	yes	yes	no	yes	15 minutes
raccoon 4	39.25lbs	male	11 minutes	yes	yes	no	no	11 minutes
raccoon 5	22.50lbs	male	40 minutes	yes	yes	yes	no	---
raccoon 6	16.50lbs	male	45 minutes	yes	yes	yes	yes	---

* not part of the control measures on substation but part of the containment fence

used tie wrap in corner*
missing tie wrap

Table 2. Summary of findings from observations of challenges to control measures by squirrels.

ANIMAL	TIME ACTIVE	CHALLENGES TO:			ESCAPE:	
		bottom of fence	upper fence	gate	outer fence	how escaped
black squirrel 1	65 minutes	yes	yes	no	yes	65 minutes
black squirrel 2	45 minutes	yes	yes	no	yes	1 1/4-inch gap between fence and gate
black squirrel 3	75 minutes	yes	yes	yes	no	---
black squirrel 4	15 minutes	yes	yes	no	yes	---
fox squirrel	30 minutes	yes	yes	no	no	---
red squirrel	6 minutes	yes	yes	no	yes	6 minutes
						used hole in top of outer fence*

*not part of the control measures on substation but part of the containment fence

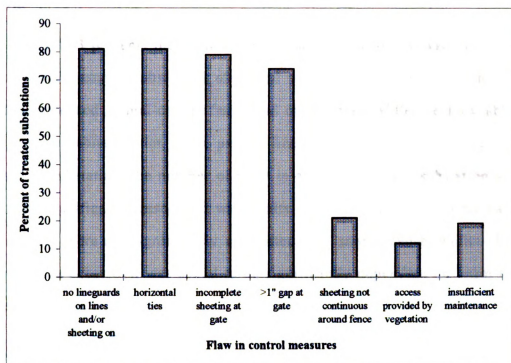


Figure 7. Percentages of treated substations with various flaws in control measures.

Characterization of Substations

Tests of Association

Table 3 presents the results of chi-square and Fisher's exact tests for homogeneity among substations classified on the basis of whether or not they had experienced animal-caused faults and on the basis of the field variables (vegetative habitat, water, nests, profile, beam structure). The distance of water from the substation, the number of nests in a substation, and substation structure were all significantly associated with faults ($p < 0.10$). All of the other variables considered were not significantly associated with animal-caused faults. Physical profile of a substation was found to be significantly dependent on beam type (Fisher's exact test, $p < 0.001$).

Results of Fisher's exact test for associations between substations experiencing faults caused by different types of animals and the field variables are shown in Table 4. The presence or absence of habitat within 50m of the substation was not uniform across the different animals causing faults. No other associations were significant ($p < 0.10$).

Table 5 summarizes the results of chi-square and Fisher's exact tests of association for the field variables across substations experiencing faults caused by different animals and those not experiencing faults. Significant associations were found between substations experiencing squirrel-caused faults versus those not experiencing faults and the following field variables: presence or absence of habitat, habitat classified in three hypothesized categories, the number of nests in a substation, and the beam type and size of the substation. The distance of water from a substation was significantly associated with raccoon-caused faults, and the number of nests in a substation was significantly associated with squirrel and bird-caused faults.

Table 3. Results of chi-square tests and Fisher's exact test for associations between animal-caused faults and field variables.

Response Variable Levels	Field Variable (levels)	Chi-square value (p)	Fisher's Exact Test: 2-tail p
not faulted, faulted	Vegetative habitat (none, present)	2.353 (0.125)	---
not faulted, faulted	Vegetative habitat (0, 14, 23) ^a	2.626 (0.269)	---
not faulted, faulted	Vegetative habitat (0, 1, 2a, 2b, 3, 4) ^b	3.754 (0.585)	---
not faulted, faulted	Water (0, 1, 2) ^c	5.957 (0.051)*	---
not faulted, faulted	Nests (0, 1, 2, 3, >4)	16.393 (0.003)*	---
not faulted, faulted	Profile (1, 2) ^d	2.435 (0.119)	---
not faulted, faulted	Structure (1, 2, 3, 4, 5) ^e	not valid	0.019*

*Significant association (P<0.10)

^a 0 : no vegetative habitat within 50m of substation

14: vegetative habitat within 50m on one or all sides of substation

23: vegetative habitat within 50m on two or three sides of substation

^b 0 : no vegetative habitat within 50m of substation

1 : vegetative habitat within 50m of substation on one side

2a: vegetative habitat within 50m on two adjacent sides of substation

2b: vegetative habitat within 50m on two opposite sides of substation

3 : vegetative habitat within 50m on three sides of substation

4 : vegetative habitat within 50m on all sides of substation

^c 0 : no water within 150m of substation

1 : water within 50m of substation

2 : water >50m but within 150m of substation

^d 1 : substation components <7m from the ground

2 : substation components >7m from the ground

^e 1 : L-shaped beams / structure $\leq 100\text{m}^2$ 2 : L-shaped beams / structure $> 100\text{m}^2$

3 : S-shaped beams

4 : combination of L and S-shaped beams

5 : wooden poles

Table 4. Results of chi-square tests and of Fisher's exact test for associations between types of animals causing faults and field variables.

Response Variable Levels	Field Variable (levels)	Chi-square value (p)	Fisher's Exact Test: 2-tail p
squirrel, raccoon, bird	Vegetative habitat (none, present)	not valid	0.093*
squirrel, raccoon, bird	Vegetative habitat (0, 14, 23) ^a	not valid	0.257
squirrel, raccoon, bird	Vegetative habitat (0, 1, 2a, 2b, 3, 4) ^b	not valid	0.339
squirrel, raccoon, bird	Water (0, 1, 2) ^c	not valid	0.113
squirrel, raccoon, bird	Nests (0, 1, 2, 3, >4)	not valid	0.758
squirrel, raccoon, bird	Profile (1, 2) ^d	not valid	0.375
squirrel, raccoon, bird	Structure (1, 2, 3, 4, 5) ^e	not valid	0.133

*Significant association (P<0.10)

^{a,b,c,d,e} see Table 3

Table 5. Results of chi-square tests and of Fisher's exact test for associations between substations experiencing faults by different types of animals and those not experiencing faults across field variable levels.

Response Variable Levels	Field Variable (levels)	Chi-square value (p)	Fisher's Exact Test: 2-tail p
none, squirrel	Vegetative habitat (none, present)	4.489 (0.034)*	—
none, squirrel	Vegetative habitat (0,14,23) ^a	4.722 (0.094)*	—
none, squirrel	Vegetative habitat (0,1,2a,2b,3,4) ^o	4.823 (0.438)	—
none, squirrel	Water (0,1,2) ^o	not valid	0.168
none, squirrel	Nests (0,1,2,3,>4)	not valid	0.023*
none, squirrel	Profile (1,2) ^a	2.594 (0.107)	—
none, squirrel	Structure (1,2,3,4,5) ^o	not valid	<0.001*
none, raccoon	Vegetative habitat (none, present)	0.000 (0.994)	—
none, raccoon	Vegetative habitat (0,14,23) ^a	0.725 (0.696)	—
none, raccoon	Vegetative habitat (0,1,2a,2b,3,4) ^o	not valid	0.490
none, raccoon	Water (0,1,2) ^o	not valid	0.017*
none, raccoon	Nests (0,1,2,3,>4)	not valid	0.346
none, raccoon	Profile (1,2) ^a	0.046 (0.830)	—
none, raccoon	Structure (1,2,3,4,5) ^o	not valid	0.175
none, bird	Vegetative habitat (none, present)	not valid	0.633
none, bird	Vegetative habitat (0,14,23) ^a	not valid	0.875
none, bird	Vegetative habitat (0,1,2a,2b,3,4) ^o	not valid	0.751
none, bird	Water (0,1,2) ^o	not valid	1.000
none, bird	Nests (0,1,2,3,>4)	not valid	0.076*
none, bird	Profile (1,2) ^a	not valid	0.182
none, bird	Structure (1,2,3,4,5) ^o	not valid	0.754

*Significant association ($p < 0.10$)

^{a,b,c,d,e} see Table 3

Spatial Arrangement of Vegetative Habitat

Comparisons between categories of the spatial arrangement of habitat around a substation and the percent of substations experiencing faults are shown in Figures 8-12. Of substations with no vegetative habitat present within 50m 21% had experienced animal-caused faults and 7% had experienced squirrel-caused faults. Of substations with vegetative habitat within 50m 31% experienced animal-caused fault and 17.5% experienced squirrel-caused faults. For substations with habitat on one or four sides within 50m, 30% had experienced animal-caused faults and 16% had experienced squirrel-caused faults. For substations with habitat on two or three sides within 50m, 33% experienced animal-caused faults and 18% had experienced squirrel-caused faults.

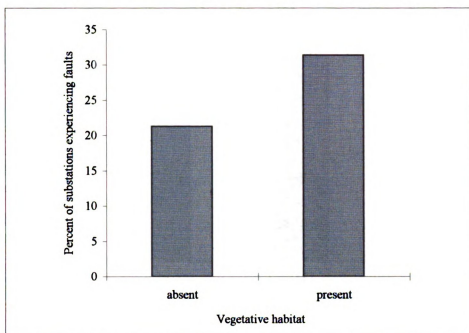


Figure 8. Percent of substations experiencing animal-caused faults in locations with and without vegetative habitat.

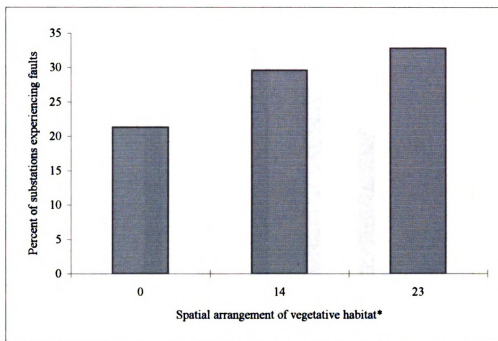


Figure 9. Percent of substations experiencing animal-caused faults in modified categories of spatial arrangement of habitat.

***Categories for the spatial arrangement of vegetative habitat:**

0 : no vegetative habitat within 50m of substation

14 : vegetative habitat within 50m on one or on all sides of substation

23 : vegetative habitat within 50m on two or three sides of substation

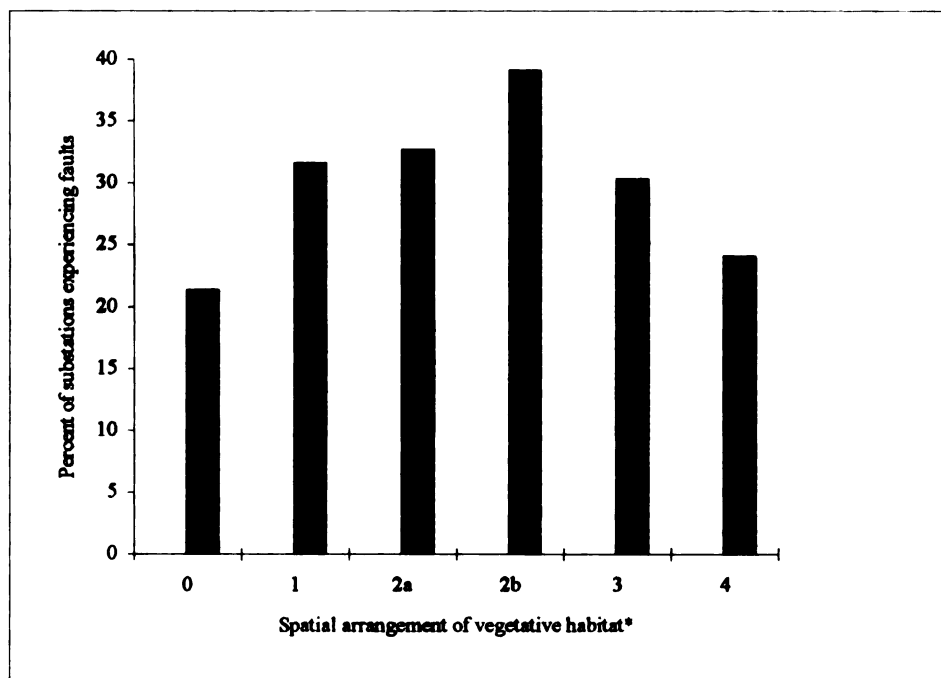


Figure 10. Percent of substations experiencing animal-caused faults in the different categories of the spatial arrangement of vegetative habitat.

***Categories for the spatial arrangement of vegetative habitat:**

- 0 : no vegetative habitat within 50m of substation**
- 1 : vegetative habitat within 50m on one side of substation**
- 2a : vegetative habitat within 50m on two adjacent sides of substation**
- 2b : vegetative habitat within 50m on two opposite sides of substation**
- 3 : vegetative habitat within 50m on three sides of substation**
- 4 : vegetative habitat within 50m on all sides of substation**

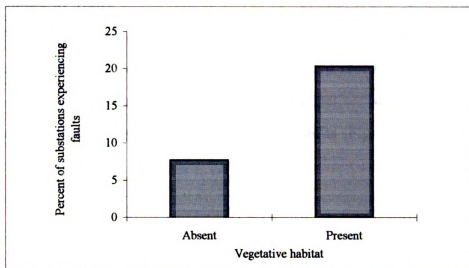


Figure 11. Percent of substations experiencing squirrel-caused faults in locations with and without vegetative habitat.

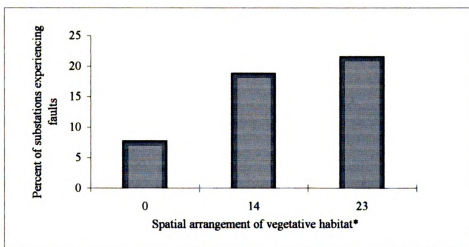


Figure 12. Number of substations experiencing squirrel-caused faults and of those not experiencing faults in modified categories of spatial arrangement of vegetative habitat.

*Categories for the spatial arrangement of vegetative habitat:

0 : no vegetative habitat within 50m of substation

14 : vegetative habitat within 50m on one or on all sides of substation

23 : vegetative habitat within 50m on two or three sides of substation

Distance of Water

For substations that had no water within 50m of the substation, 28% had experienced animal-caused faults and 6% experienced raccoon-caused faults. Of substations that had water within 50m, 46% had experienced animal-caused faults and 21% had experienced raccoon-caused faults (Fig. 13-14).

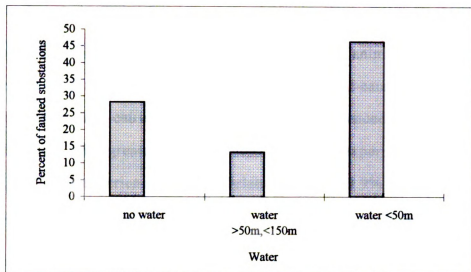


Figure 13. Percent of substations experiencing animal-caused faults in each of the categories of the distance of the substation from water.

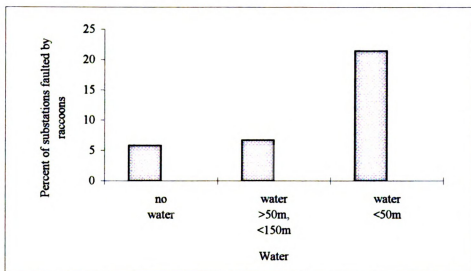
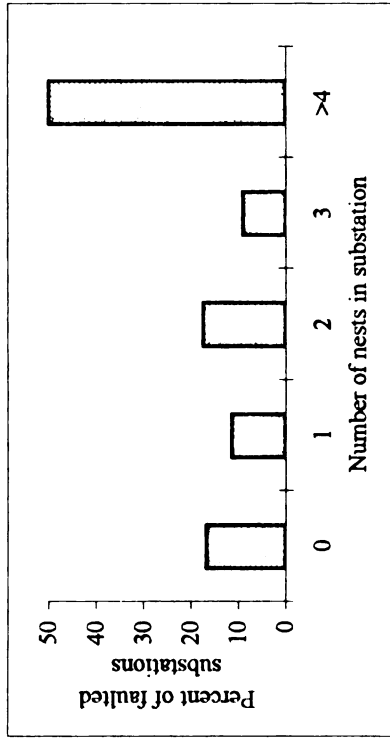


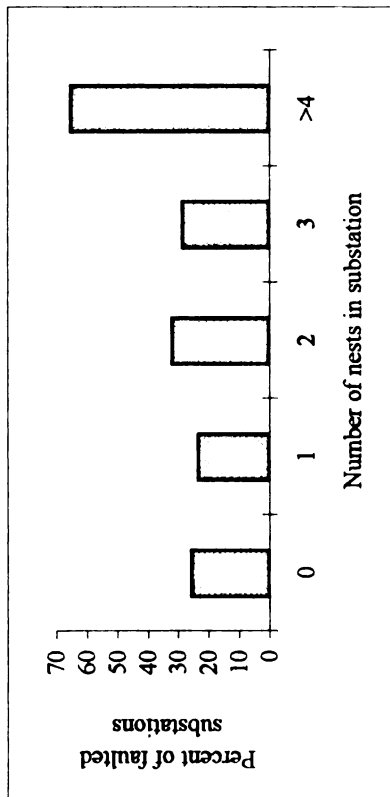
Figure 14. Percent of substations experiencing raccoon-caused faults in each of the categories of the distance of the substation from water.

Number of Bird Nests

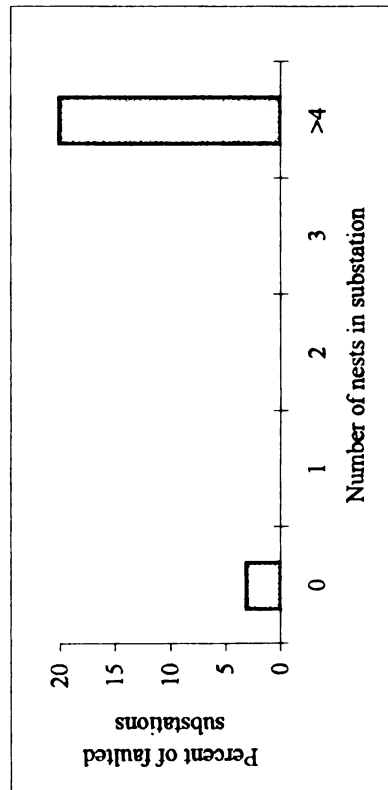
Figure 15 presents comparisons between the number of nests in a substation and the percent of substations experiencing animal-caused faults. Of substations with no nests, 26% had experienced animal-caused faults, 15% had experienced squirrel-caused faults, and 2% had experienced bird-caused faults. Of substations with greater than four nests, 65% had experienced animal-caused faults, 35% had experienced squirrel-related faults, and 9% had experienced bird-caused faults.



B.



A.



C.

Figure 15. Percent of substations experiencing animal-caused faults (A), squirrel-caused faults (B), and bird-caused faults (C) by the number of nests in a substation.

Profile

Figure 16 shows the comparison of the percent of substations faulted by animals for low profile ($<7\text{m}$) and high profile ($>7\text{m}$) substations. Twenty-two percent of low profile substations experienced animal-caused faults, and 32% of high profile substations experienced animal-caused faults.

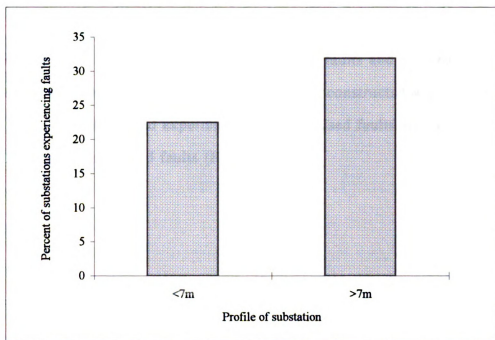
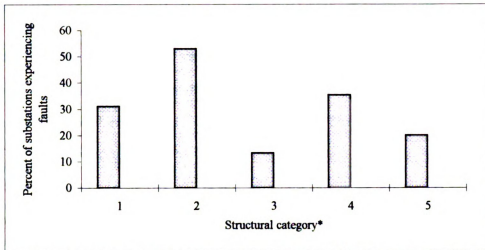


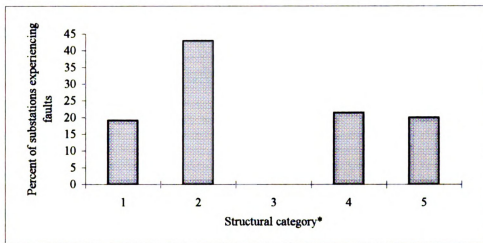
Figure 16. Percent of substations experiencing animal-caused faults in the two categories of profile.

Substation Structure

Of substations that were greater than 100m² and constructed with L-shaped beams 53% had experienced animal-caused faults and 35% had experienced squirrel-caused faults. For substations constructed with S-shaped beams (I-beams) 13.3% had experienced animal-caused faults and none experienced squirrel-caused faults (Fig. 17).



A.



B.

Figure 17. Percent of substations experiencing animal-caused faults (A) and squirrel-caused faults (B) by structural categories.

*Structural categories:

- 1: L-shaped beams / structure $\leq 100\text{m}^2$
- 2: L-shaped beams / structure $> 100\text{m}^2$
- 3: S-shaped beams
- 4: combination L and S-shaped beams
- 5: wooden poles

Logistic Regression Model

The maximum likelihood estimates and related statistics for a logistic regression analysis including all variables used to classify substations are shown in Table 6. The model based on these estimates correctly predicted 56% of 50 samples that had not been used to create the model. The highlighted variables in table 6 are the ones used in the logistic regression analysis that included only the significant factors ($P < 0.10$). This model again correctly predicted 56% of 50 samples not used to created the model (Table 7). The Hosmer and Lemeshow Goodness-of-fit tests for the models indicated that both models fit since the tests were not significant ($p = 0.57$, $p = 0.60$).

Table 6. Regression coefficients (maximum likelihood estimates) and related statistics from logistic regression analysis.

Variable	DF	Parameter Estimate	Standard Error	Wald Chi-Square	Pr > Chi-Square	Standardized Estimate
intercept	1	-2.4993	0.7332	11.6199	0.0007	.
habitat (0,1)	1	0.5704	0.4392	1.6864	0.1941	0.129183
water <50m	1	0.0364	0.5595	0.0042	0.9482	0.005618
water >50m	1	-1.8335	1.1749	2.4355	0.1186	-0.240262
1 nest	1	0.4035	0.4351	0.8598	0.3538	0.088588
2 nests	1	0.2109	0.5673	0.1382	0.7101	0.034013
3 nests	1	-0.112	0.8357	0.018	0.8934	-0.01365
>4 nests	1	1.6508	0.4964	11.0605	0.0009*	0.255005
profile	1	0.6714	0.3974	2.8541	0.0911*	0.165357
L-beams / <100m ²	1	0.8661	0.6396	1.8339	0.1757	0.226985
L-beams / >100m²	1	1.2145	0.5789	4.401	0.0359*	0.159152
combination	1	1.1815	0.8535	1.9164	0.1663	0.149535
wooden poles	1	1.174	0.882	1.772	0.1831	0.148586

* Significant factor (p<0.10)

Table 7. Matrix of predictions of damage of 50 substations by logistic regression models using all variables and significant variables only (both models have the same matrix).

	Damage predicted	No damage predicted
Correct	4	24
Incorrect	1	21

DISCUSSION

Examination of Records of Animal-caused Faults

The data provided by Consumers Power from reports of animal-caused faults to electric substations between 1988 and 1993 helped to define the general nature of the problem of animal damage. Over the six year period 121 incidents of animal-caused faults occurred in 88 of the 1,177 transmission and distribution substations owned by Consumers Power. There could be any number of reasons that animals entered the substations. They could have been searching for food, storing food, searching for nesting sites, playing, escaping from predators, travelling, or satisfying curiosity.

According to the records, squirrels accounted for 57% of all animal-caused faults. These results correspond very well to those of Enck (1989) who found that 55% of all animal-caused faults were caused by squirrels. Forty-two percent of all damage caused by squirrels occurred in June, September, and October. Similarly, in a study of fox squirrel damage to electrical transformers, Hamilton (1987) found that 34% of all outages caused by squirrels occurred in June and October during the morning hours. The results reflect the seasonal and daily activity patterns of squirrels, such as foraging activity and home range expansion of young squirrels born in early spring or in the summer. Mid-May and early October were identified by Thompson and Thompson (1980) as two annual peaks in the foraging activity of urban grey squirrels, and maximum home range expansion for grey squirrels in Toronto, Canada was found to be at

the highest levels in the middle of June and in the middle of October (Thompson 1978).

Because squirrels are known to be highly active during the morning hours just after sunrise (Brown and Yeager 1945, Fogl 1982), it was not surprising that 70% of squirrel caused faults occurred between 6:00AM and noon. Grey squirrels have typically been found to have a bimodal daily activity pattern with most activity occurring in the morning and late afternoon, particularly in non-winter months (Brown and Yeager 1945, Thompson 1977, Fogl 1982). Fox squirrels, on the other hand, typically exhibit a unimodal daily activity pattern with activity occurring early in the morning and through midday (Brown and Yeager 1945, Cauley 1974, Fogl 1982). The reason that most squirrel damage occurs in the morning might involve the overlap in daily activity patterns of fox and grey squirrels.

Raccoons were found to have caused 21% of the reported animal-caused faults, which was a higher percentage than the 12% found by Enck (1989). Damage caused by raccoons in April, May, and August accounted for 65% of damage by raccoons over all months. No raccoon caused damage occurred in November through February. As with the squirrel related results, these findings apparently reflect the activity patterns of raccoons. In a radio-tracking study of raccoons in Minnesota, Schneider (1973) observed that by early April raccoons stopped using their winter dens and became more active than they had been in the previous winter months. Young raccoons born in May became independent around August, and all activity stopped at the end of November, when the raccoons denned for the winter. Hoffman and Gottschang (1977) reported that raccoons in suburban Ohio were most active during May, July, and August. The highest raccoon capture rate was found in May, and raccoon trapping rates

dropped off substantially in November through April. Furthermore, raccoon damage was most common between the hours of 9:00PM and 6:00AM. Once again, the results coincide well with the peak daily activity patterns of raccoons (Cauley 1974, Schinner and Cauley 1974).

Birds caused 7% of animal caused damage. The Consumers Power records did not indicate what species of birds were involved in each incident. Because this information was not available and because the number of incidents of bird damage were relatively low (9), it is difficult to draw any conclusions about seasonal or temporal patterns. Birds probably caused faults by contacting two energized components simultaneously (phase-to-phase fault), which seems to occur infrequently (Enck 1989). The low numbers of bird caused faults suggests that this kind of damage should not be a major focus in preventing animal damage to substations. However, other factors that are related to the presence of birds in substations, such as nests, might impact the susceptibility of the substation to damage. The impact of nests in a substation is discussed in the characterization of damaged versus undamaged substations.

Finally, the Consumers Power records provided information about direct and indirect costs incurred because of animal-caused faults. One cost to the company is the loss caused by damage to substation equipment. The most commonly damaged and replaced items in a substation were fuses (54%), and insulators were the second most damaged item (10%). Other costs to the company include the revenue lost while power is out and the indirect cost of reduced consumer confidence because of the loss of service to customers during an outage. Outages occurred in all but three of the 121 reported faults. The number of customers affected by an outage ranged from 1 to 3,979, and an average of 2,511 customers per outage were affected. The amount of time that

a fault lasted was one hour and 46 minutes on average and ranged from 15 minutes to 14 hours and 14 minutes. These results show that the costs of animal-caused fault are potentially very high. Enck and Brown (1989) estimated combined direct and indirect costs of animal-caused faults for six utility companies in New York state to be as high as \$10 million over an eight year period.

Evaluation of Control Measures

Observations of raccoons and squirrels at the animal proofed training facility indicate that control measures are effective if correctly and completely applied, but proper application is critical. The only raccoon to thwart the control measures (not via the outer containment fence) was able to find the only missing tie on the polycarbonate barrier in about eleven minutes. The raccoon was then able to pull the polycarbonate away from the fence and climb under it until he reached the top of the fence. The fact that it took only eleven minutes for the raccoon to find the missing tie suggests that even one minor flaw is enough to make the substation fence penetrable. However, it is important to recognize that the observed raccoons were trapped between the outer and inner fences, which would not be the situation in a natural setting.

Of the squirrels observed at the facility, only one, a black squirrel, penetrated the control measures. As with the raccoon, the squirrel found a flaw in the animal proofing. This time it was a $1\frac{5}{8}$ -inch gap between the fence and the gate. It took the squirrel about 65 minutes to find and escape through the hole. Consumers Power specifies in their animal proofing measures that there should be no more than a 1-inch gap. Here again is evidence that the correct application of damage control measures is important if they are to be entirely effective.

In addition to these two escapes, the red squirrel and one raccoon escaped by way of the outer polycarbonate fence. While these animals did not escape through the animal-proofing, they demonstrated both the agility of the animals and their ability to find obscure escape routes. For example, the raccoon climbed the fence and was able to stretch just far enough to use a tie to pull himself to the corner between the inner and outer fences and then climb out. The red squirrel escaped at the corner of the outer fence by jumping to grab a $\frac{1}{4}$ -inch hole near the top of the fence (4ft from the ground).

Although the control measures did not keep two of the animals out of the substation, they did prevent ten others from entering. Therefore, it appears that the control measures are effective but that this effectiveness is compromised by flaws in application.

The results of the field evaluation of 43 substations treated with animal proofing showed that only one of the substations was completely and correctly treated, indicating that effectiveness is not 100% at any of the other substations. Common flaws in animal proofing included: 1) polycarbonate or aluminum sheeting not applied to all poles within 25m of the substation and/or no lineguards on lines entering the substation (81% of treated substations), 2) ties applied horizontally (81%), 3) polycarbonate or aluminum sheeting not applied correctly at gates (79%), and 4) gaps greater than 1inch at the gate to the substation (74%). Some of the flaws represent old control measures that were applied under different guidelines of animal proofing than currently being used. For example, ties applied horizontally have been found by Consumers Power to be more susceptible to access by squirrels than ties that are applied vertically. Therefore, in newly treated substations the ties are affixed vertically.

Although these partially treated substations are probably less susceptible to damage, they are not entirely safe from it. The effectiveness of treatment will depend in part on how badly an animal wants to get into the substation. However, the observations at the training facility indicate that if all control measures are precisely and thoroughly applied, animals will be prevented from entering a substation.

Characterization of Substations

One way to aid in the prevention of animal-caused faults at substations is to understand what makes the substation susceptible to these faults. This approach narrows the scope of the problem by identifying characteristics to be targeted with preventative measures and by identifying substations most likely to be damaged based on the set of characteristics.

In the comparison of substations that had been damaged and those not damaged, three of the variables measured in the field analysis were significantly associated with faults ($p < 0.10$). These variables were beam construction (Fisher's exact test, $p = 0.019$), distance of water from the substation (chi square test, $p = 0.051$), and number of nests in the substation (chi square test, $p = 0.003$).

From results of the Fisher's exact test and from examination of the frequency table for this variable, the substation structures most responsible for susceptibility to damage are those involving L-shaped beams, particularly those that cover an area greater than 100m^2 . The reason for this beam structure being more susceptible could be because these structures are easily climbed by raccoons and squirrels and because they provide good nesting locations for birds. Damage caused by squirrels was significantly associated with beams structure ($p < 0.001$), suggesting that this may be a particularly important factor

to consider when trying to prevent squirrel damage. Beam structure was not significantly associated with damage by raccoons or by birds although sample sizes were much smaller for these two categories.

The physical profile of the substation was not found to be significantly different between substations that had been faulted and those that had not, although the chi square p-value was 0.119. Faults caused by squirrels and birds were more likely to be affected by profile than those caused by raccoons ($p = 0.830$) but none were significant. Enck (1989) reported that 81% of animal-caused faults occurred in high profile substations ($>25\text{ft}$) but could not make definite conclusions about susceptibility because the system-wide distribution of low and high profile substations was not known and because of inconsistencies in the definition of high and low profile used by data providers. In the present study 78% of animal-caused faults occurred in high profile substations which coincides with the results found by Enck. However, 37% of the 204 high profile substations ($>7\text{m}$) experienced damage, whereas 22.5% of the 80 low profile substations ($<7\text{m}$) experienced damage. The latter results suggest that the effect of profile on susceptibility is probably not as marked as suggested by Enck's results. Furthermore, because beam type and physical profile are significantly related, it is possible that the association between faults and profile is just an artifact of the association between beam type and animal-caused faults.

The effect on damage of the distance of water from the substation was significant for damaged versus undamaged substations ($p = 0.051$). Faults caused by squirrels and by birds were not significantly associated with distance from water, but raccoon-caused faults were significantly associated with the distance of water from a substation ($p = 0.017$). Substations within 50m of

water seem to be particularly susceptible to faults caused by raccoons. These results reflect the fact that water is an important component of raccoon habitat. For example, in a study by Soneshine and Winslow (1972), 98% of raccoon captures in one study area were within 121m of water. The significant association of water with damage suggests that proximity of water to a substation should be a factor that is considered, where reasonable, when building new substations and could provide an indication of which substations will experience faults in the future.

The results show that the presence of nests in a substation is significantly associated with damage to the substation ($p = 0.003$). The presence of at least four nests in a substation seems to be particularly indicative of damage to the substation. Approximately 18% of faulted substations had at least 4 nests, but only about 4% of substations that had not experienced a fault had at least 4 nests. Squirrel and bird-related faults were significantly associated with the number of nests at a substation but raccoon-related faults were not.

The connection between the number of nests in a substation and bird damage is obvious, but the connection with squirrel damage is not as obvious. Nests might attract foraging squirrels to a substation. However, it is also likely that squirrel damage and the number of nests are associated because of some habitat or structural component to which they are both correlated. Independence of the variables in the study was difficult to analyze because sample sizes for certain combinations were extremely low. However, there were no obvious associations between nests and the other variables. Therefore, if nests are correlated with some habitat or structural component, it could be one that was not recorded in this study. An evaluation of the species of birds nesting in substations might be helpful in determining the cause of the

association between nests and damage because the species that have been found to nest in substations, such as sparrows, robins, starlings, and blackbirds, occur in different habitats.

The final variable considered in the field analysis was vegetative habitat. A study by Enck and Brown (1989) found no correlation between surrounding habitat and the number of faults at a substation. However, the relationship between habitat and wildlife damage may not have been fully described by the study. One possible reason for these findings is that the correct habitat variables were not used.

Another possible reason that Enck and Brown found no correlation between habitat and wildlife damage is that there is a non-linear relationship between the amount of habitat surrounding the substation and the amount of damage to the substation. For example, in areas with few trees there may be little damage to substations because there are no squirrels in the area. There may also be little damage in areas with many trees because the animals would not need to use the substation as a travel route and would have plenty of available habitat. In areas with moderate amounts of trees, the most damage would be seen because animals would use substations for activities such as travelling or searching for food or shelter.

A final possibility is that the spatial arrangement of the vegetative habitat around a substation may be a significant factor in wildlife damage to the substation. For example, Layne (1954) observed that red squirrels often use hedgerows as travel lanes. If a hedgerow were interrupted by a substation, it would be easy to imagine that a squirrel, or any animal using the travel route, might enter the substation more often than if the hedgerow were continuous and away from the substation. Similar relationships between the spatial arrangement

of the habitat surrounding a substation and use of a substation by an animal might be predicted for other animals.

The results of the present study showed a significant association between squirrel-related faults and the presence or absence of vegetative habitat ($p=0.0034$). Approximately 91% of substations faulted by squirrels had vegetative habitat on at least one side, and 76% of substations not experiencing faults had vegetative habitat on at least on side. Additionally, it had been hypothesized that damage would occur most often in substations with vegetative habitat on two or three sides of the substation, less often in substations with vegetative habitat on one or four sides, and least often in substations without any vegetative habitat surrounding it. The data from the field generally reflected this hypothesis, although the relationship between the three generalized categories and animal-caused faults was not significant. When damage by squirrels was analyzed for substations placed in the three habitat categories, a significant relationship was found ($p = 0.094$). None of the categorizations of vegetative habitat were significantly related to faults by raccoons or birds. The fact that a significant relationship was found for squirrels but not for the other animals probably reflects that the hypothesis that established the habitat classifications was based largely on the predicted behavior of squirrels. The smaller sample sizes for raccoons and birds could also have influenced the analysis.

The above results suggest that there is a relationship between vegetative habitat and animal-caused faults to substations. In particular, squirrels are most likely to cause faults in substations that are surrounded by vegetative habitat on two or three sides and least likely to cause faults in substations with no vegetative habitat within 50m. These findings contradict the conclusion by

Enck (1989) that substation damage was not related to the surrounding habitat. Methods of collecting and analyzing habitat data differed considerably between that study and this one and might explain the discrepancy. By Contrast, Hamilton (1987) found that the number of leaf nests near electrical transformers in Lincoln, Nebraska was significantly greater where squirrel-caused outages were a problem and that the mean basal area of mulberries within 2m of power equipment or power poles was several times greater at problem sites.

To analyze the capability of the habitat and structural variables considered in this study to predict damage to electric substations, a logistic regression model was created from 234 of the substations classified in the field analysis. First, a model was created that included all of the variables in the classification of visited substations. Fifty substations not used to create the model were randomly selected from the sampled substations and were used to test the predictive ability of the model. Substations were classified as faulted if the predicted probability of being faulted was greater than 0.50. The model correctly predicted whether or not a substation had experienced an animal-caused fault for only 56 % of the 50 samples. Because only four of the independent variable were significant at $p < 0.10$, the model was simplified to include only these variables. Like the model using all variables, this model fit the data ($p = 0.6005$) and correctly predicted 56% of the 50 sampled substations used to test the models. The low predictive ability of these models probably has to do with the fact that the two most significant predictors (>4 nests in a substation and L-shaped beams with heavy latticework) occurred in only six of the 50 substations used to test the models, and none of the 50 substations had both characteristics.

In theory, this type of model could be used to predict whether or not a substation will be damaged in the future, but the model would have to be substantially improved by considering additional explanatory variables. However, it is likely that a highly predictive model would be extremely difficult to create. Regardless of whether the model is used to predict faults, it illustrates how the different habitat and structural components associated with a substation can be used in combination to assess the likelihood of the substation experiencing an animal-caused fault.

Recommendations

Several recommendations about how to prevent animal-caused faults can be made based on the results of this study. First, certain characteristics of the habitat and of the structure of a substation should be considered when a new substation is built. Building a substation in areas within 50m of lacustrine or riverine habitat should be avoided. A good location for a substation would probably be one with very few trees and shrubs and no water within 50m. In addition, if possible, substations should be built with beams that are least conducive to climbing and nesting activities. The structural characteristics of the substations owned by Consumers Power that are most likely to be connected with animal damage are large L-shaped beam structures. Because the choice of sites and materials for a new substation are likely to be limited and habitat alteration may not be possible, preventative measures that can be applied to existing substations is probably more practical.

Observations of challenges to the control measures used by Consumers Power established that the measures are effective in keeping raccoons and squirrels out of a substation if applied properly. Inspection of treated substations by informed personnel might help to insure that the measures have been thoroughly and precisely applied. The control measures could be applied to substations that have one or more of the characteristics that were found to be associated with animal-caused faults. These substations would be ones that are composed of L-shaped beams and cover an area larger than about 100m², substations that are located within 50m of water, substations with vegetative habitat within 50m on two or three sides, and substations that have at least four bird nests in them. A substation having just one of these attributes probably

does not warrant animal proofing, although the presence of all of the characteristics might warrant it if the costs of animal proofing are not too large. Currently at Consumers Power, the decision about whether or not to animal proof depends on how many times and how often the substation has been damaged. These criteria could be incorporated with knowledge about structural and habitat characteristics to make this decision in the future.

The association of damage with nests might suggest regular removal of nests or a control measure that prevented nesting. Most nests were located in corners where perpendicular beam structures meet, and so any object that would obstruct the corner might help to prevent nesting in the substation. The air spaces in the transformer assembly were also common nesting sites and therefore could be targeted with control measures. However, it is also possible that the nests themselves are not the problem but are related to some unknown characteristic that affects the susceptibility of the substation. In this case the only way to prevent damage would be to use the traditional control measures because the actual source of susceptibility is not known. The investigation of factors that are potentially related to the number of nests in a substation would help to address this problem.

CONCLUSION

The prevention of wildlife damage to electric substations is aided by an understanding of what factors are responsible for the susceptibility of a substation to damage and of what preventative measures will be most effective. The results of this study provide evidence that the susceptibility of electric substations to animal-caused faults is related to the type of beams used in the substation, the size of the structure, distance of the substation from water, and the number of bird nests in the substation. The presence and spatial arrangement of habitat components was significantly associated with squirrel-caused faults, which accounted for 57% of all of the animal-caused faults recorded.

The application of the control measures currently being used by Consumers Power should be effective in keeping raccoons and squirrels from entering the substation, provided that the application has been done correctly and completely. The decision about which substations to treat with control measures should involve the evaluation of the structural and habitat characteristics of a substation in addition to the evaluation of records of previous damage to a substation. This approach should help to more successfully prevent wildlife damage to substations.

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