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RESEARCH REPORT

AN INVESTIGATION INTO THE USE OF ROAD DRAINAGE STRUCTURES BY WILDLIFE IN MARYLAND

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16. Abstract

The research team documented culvert use by 57 species of vertebrates with both infra-red motion detecting digital game cameras and visual sightings. Species affiliations with culvert characteristics were analyzed using χ^2 statistics, Canonical Correspondence Analysis (CCA), ANOVA, and *t*-tests for 12 species (northern raccoon, Virginia opossum, domestic cat, woodchuck, great blue heron, red fox, humans, white-tailed deer, gray squirrel, Norway rat, gray fox, and white-footed or deer mouse) that occurred in more than 30 culverts. Culvert width and length were the most important variables according to CCA. Nearly all of these 12 species exhibited greater use of culverts with lower mean water depth, except for great blue heron, which used culverts that had deeper water (P = 0.014) more frequently. White-tailed deer (n = 1,903 in 63 culverts) were not strongly associated with a particular culvert shape ($\chi^2 = 5.589$, 2 df, $P = 0.061$) or substrate type ($\chi^2 = 7.462$, 5 df, $P = 0.188$). White-tailed deer used culverts less often when there was no fence on either side of the highway ($\chi^2 = 26.491$, 5 df, $P < 0.001$). The number of road-killed deer was generally less in areas receiving high use of culverts by deer, although there were notable exceptions. White-tailed deer used culverts in the Maryland Piedmont region more frequently ($F_{[3, 261]}$ = 5.995, $P = 0.001$). Northern raccoons were the most prevalent species in the camera survey, occurring in 246 of the 265 (93%) sampled culvert cells. Green frogs were the most abundant herptile species, sighted in 38 culverts. Box culverts were the most frequently used type of culvert for nest building by both barn swallow ($\chi^2 = 7.474$, 1 df, $P = 0.006$) and eastern phoebe ($\chi^2 = 18.292$, 1 df, $P < 0.001$). Our results can be used to better design or retrofit culverts to improve wildlife-habitat connectivity and reduce wildlife-vehicle collisions.

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INTRODUCTION

Habitat fragmentation by roads is perhaps the most pervasive form of direct anthropogenic terrestrial habitat destruction (Spellerberg 1998, Forman et al. 2003). Roads result in habitat loss, degradation of gene flow, and direct mortality of wildlife by vehicle collisions (Forman and Alexander 1998, Spellerberg 1998, Trombulak and Frissel 2000, Forman et al. 2003, Watson 2005). There are 3.85 million miles (6.2 million kilometers [km]) of paved roads in the United States (U.S.), with their edge effects influencing the ecology of 15-20% of the land area (Forman and Alexander 1998). The State of Maryland has 68,694 lane miles (110,552 lane km) of paved roads (OHPI 2007: Table HM-60). Vehicle traffic on roads has a direct effect on mortality and behavior of sensitive wildlife species by altering movement patterns, home range, reproductive success, escape response, and physiological state (Trombulak and Frissel 2000). As the demand for mitigation of effects caused by road development increases, managers seek new understanding and methods to restore fragmented wildlife populations (Trombulak and Frissel 2000, Forman et al. 2003).

Road drainage structures, also known as culverts, are principally constructed for the purpose of alleviating erosion by channeling intermittent and perennial streams under roadways (SHA 2003). Existing culverts are also used by wildlife for passage under roads, thereby mitigating many of the detrimental effects of roads by enabling wildlife movements, increasing habitat connectivity, and potentially reducing wildlife-vehicle collisions (Rodriguez et al. 1996, Clevenger and Waltho 2000, Ng et al. 2004, Aresco 2005, Grilo et al. 2008). Rising concerns about habitat fragmentation and loss and isolation of wildlife populations caused by roadways have led to the increased scrutiny of existing culverts as wildlife-habitat linkages (Foster and Humphrey 1995, Romin and Bissonette 1996, Clevenger and Waltho 2000, Clevenger et al. 2001*a*, Forman et al. 2003, Ascensão and Mira 2007). Existing culverts are known to be used by numerous species in a variety of ecosystems around the world, such as wolves (*Canis lupus*), cougars (*Puma concolor*), black bears (*Ursus americanus*), grizzly bears (*Ursus arctos horribilis*), deer (*Odocoileus* sp.), elk (*Cervus elaphus*), and moose (*Alces alces*) in Canada (Clevenger and Waltho 2000); white-tailed deer (*Odocoileus virginianus*), northern raccoons (*Procyon lotor*), bobcats (*Lynx rufus*), endangered panthers (*Puma concolor coryi*), alligators (*Alligator mississippiensis*), and black bear in Florida (Foster and Humphrey 1995); and red fox (*Vulpes vulpes*), badger (*Meles meles*), mongoose (*Herpestes ichneumon*), and genet (*Genetta genett*a) in Portugal (Grilo et al. 2008). Specially designed culverts have been used to defragment habitat for small mammals, such as the federally threatened Preble's meadow jumping mouse (*Zapus hudsonius preblei*) (Meaney et al. 2007). In addition to mammals, culverts have been employed to mitigate a variety of herpetofauna in Florida (Aresco 2005); box turtles (*Terrapene carolina*) in Maryland (Hagood 2009); and federally-threatened bog turtles (*Clemmys muhlenbergi*) in New Jersey (Bird 2003).

Collisions between vehicles and deer cause 29,000 human injuries, 211 human fatalities, and cost nearly $1.1 billion in vehicle repairs in the U.S. annually (Conover et al. 1995). Mitigation of vehicle collisions with large mammals and the associated costs are a rising concern among civil engineers as well as wildlife managers (Conover et al. 1995, Romin and Bissonette 1996, Schwabe and Shumann 2002). Previous research concerning issues of driver safety and cost-benefit analysis in North America has focused on identifying road-kill hot spots (Bellis and

Graves 1971, Puglisi et al. 1974, Allen and McCullough 1976, Bashore et al. 1985, Hubbard et al. 2000). Culverts that are properly sized and placed under newly constructed roadbeds may reduce deer-vehicle collisions by allowing deer to pass under the road rather than over it (Clevenger and Waltho 2000, Brudin 2003, Ng et al. 2004, Donaldson 2005). Highway planners in North America and Europe have been investigating existing culvert dimensions and placement as important components of wildlife mitigation, road planning, and highway safety (Clevenger and Waltho 2000, Smith 2003, Malo et al. 2004, AZGFD 2006, Ascensão and Mira 2007).

There is an increasing need to study the actual mitigation potential and effectiveness of existing culverts (Spellerberg 1998, Hardy et al. 2003, Smith 2003). Existing culverts are passageways that can be studied to provide information about animal usage in relation to passageway dimensions and placement (Rodriguez et al. 1996, Smith 2003, Ng et al. 2004, AZGFD 2006). Our goals were to quantify the extent to which culverts are used by mesofauna and white-tailed deer (*Odocoileus virginianus*) in the State of Maryland and to assess the characteristics of the culverts and surrounding cover types most prevalent at those sites. We also sought to compare roadside deer mortality with deer use of nearby culverts to provide us with some indication of their importance in reducing deer-vehicle collisions. This study of culvert use by wildlife is the first statewide study in the Mid-Atlantic region of North America and hopefully will aid in building safer SHA highways and improving wildlife mitigation in a cost-effective manner. We anticipate that our results will offer insights into future designs of successful wildlife passageway systems, potentially reducing vehicle collisions with wildlife and repairing wildlife-habitat continuity.

STUDY AREA

We began our survey with 265 randomly-selected drainage structures, hereafter called culverts, within the State of Maryland (longitude: 75° 4'W to 79° 33'W, latitude: 37° 53'N to 39° 43'N). Maryland is a Mid-Atlantic State that spans five physiographic provinces (Paradiso 1969) from the Appalachian Plateau (highest elevation 3,359 feet [1,024 m]) to the Coastal Plain (lowest elevation, sea level 0 feet [0 m]). Average annual temperatures range from 48° F (9° C) in the extreme western uplands to 59° F (15° C) in the maritime southeast (CityData.com 2010). Average annual rainfall is around 43 inches (109 cm) and is fairly consistent across the entire state (NationalAtlas.gov 2010). Mixed mesophytic forest types are found at the highest elevations, with xeric oak (*Quercus* sp.)-hickory (*Carya* sp.) being more common in the Piedmont and oak-pine (*Pinus* sp.) in the Coastal Plain (Braun 1950). All sizable forests in the State of Maryland are secondary re-growth (Braun 1950).

We followed Stewart and Robbins (1958) division of Maryland into five biotic regions or physiographic provinces for our geographic analysis. We counted the Allegheny Mountain region and the Ridge and Valley region, as one ecologically similar region which we named the Appalachian Mountain region. We did this in order to maintain a more parsimonious sampling of the western uplands. This gave us four biotic regions. The Appalachian Mountain region is primarily rural having 170.13 inhabitants/mile^2 (USCB 2010). The Piedmont region had urban and suburban elements with a population density of 768.29 inhabitants/mile^2 (USCB 2010). The Western Shore has an urban/suburban human population density of 735.36 inhabitants/mile^2 (USCB 2010). The Eastern Shore is primarily agricultural land with a much lower human population density of 121.90 inhabitants/mile^2 (USCB 2010). Camera effort per square mile of area was nearly equal among the Appalachian Mountain, Piedmont, and Western Shore, while it was considerably less on the Eastern Shore (Table 1).

METHODS

Characteristics of Culverts and Roads

Culverts are constructed under roadways to accommodate intermittent or perennial first and second order streams. All culvert sampling sites were selected along paved state roads maintained by SHA. The SHA maintains approximately 25%, or 14,675 lane miles (23,617.1 lane km), of Maryland's paved roads (OHPI 2007: Table HM-81).

Each individual culvert is known as a cell. A culvert site may have more than one cell. We surveyed cells as individual occurrences, because our objective was to infer the importance of various cell dimensions. Culverts ranged from a minimum width and height of 0.61 m × 0.61 m to a maximum width and height of 4.57 m × 4.57 m and were distributed randomly throughout the State of Maryland. We began with 265 viable culvert cells from the originally selected 300 culvert sites, and of those we were able to continuously monitor 228 cells throughout the 2.3-year study (Table 2). These continuously monitored sites did not have any incidences of theft, vandalism, or flooding and were not otherwise rendered unsuitable for camera placement. Each culvert cell was surveyed for two weeks on a roughly seasonal rotating basis, we sampled at least twice per season over a 2.3-year period at each culvert cell (28 August 2008 to 3 January 2011). We sampled each culvert cell at least nine times.

Culverts occurred in one of three shapes; arch (Figure 1), box (Figure 2), or cylinder (Figure 3; Table 3). We identified six substrate types; silt, sand, gravel, cobble, bare corrugated steel, and concrete (Table 3). We described seven categories of fencing arrangements ranging from both sides with fencing five feet or greater in height (≥1.5 m) between the road and culvert to no fencing on either side (Table 4).

Individual culverts were measured for openness (O = width × height/length [Yanes et al. 1995]). Openness is a variable used to describe the visually apparent size of the opening on the far end of a culvert. It is believed to be an important variable affecting the passage of large mammals through culverts (Yanes et al. 1995, Clevenger and Waltho 2000, Clevenger et al. 2001*a*). We measured the distance to woody vegetation cover on both ends of the culvert and the percent visibility of the opening (i.e., lack of vegetation) on both ends. The depth of water at the camera posting site was measured during each visit. We used data provided by SHA (unpublished data 2008) concerning culvert dimensions and road characteristics, such as the amount of soil between the top of the culvert and the road bed (earth-fill height), the number of lanes, and the average daily traffic volume. Table 5 provides a complete listing of these variables and their summary values.

Culvert Use

Culvert use was documented with passive infra-red motion detecting digital cameras (Moultrie Game Spy i40 digital game camera; Moultrie Feeders, Alabaster, Alabama). Gompper et al. (2006) found that game cameras were highly effective among a variety of non-invasive methods for detecting the greatest number of species at open forest stations. Ford et al. (2009) determined that camera trapping is more efficacious than using track plates over periods of time greater than one year for reasons of allocated work hours. Our method required visiting sites twice over two weeks, while track plates would have required visitations once every three days for each site (Wolf et al. 2003). Track plates were also not suited to our mostly wet locations, which were susceptible to sporadic flooding. We did not use track plates, but we did record incidental animal tracks (Stall 1989) to cross reference species occurrence. We also kept sighting records.

We mounted cameras at the approximate midpoint of the culvert on a five inch (12.7 cm) steel angle bracket, 24 inches (61 cm) from the floor or water surface in the culvert (Figure 4). Exceptions were made when the drainage structure was too low to enter. In these situations, the camera was mounted on one end, either on a pressure treated stake or upside down from a hanging angle bracket mount. In four cases, urban culverts had only one passable end with the other leading to multiple, street-level, storm drains, instead of another passable culvert opening. The camera was then mounted in the culvert at a point estimated to be the mid-point of the road.

Cameras were set to one minute picture intervals to minimize taking pictures of the same animal twice. We counted each identifiable animal in a photograph as a single animal use of a culvert, equivalent to a crossing. Our cameras were triggered by moving heat signatures and therefore responded primarily to mammals and birds. We did make direct observations of reptiles, amphibians, and other vertebrate fauna when we visited the sites to place and remove cameras.

Data Analysis

We assumed that each culvert was independent of the others. This assumption was likely violated at 22 sites which had double-cell culverts and one which had triple cells. We retained this assumption because we wanted to analyze species use of culvert type and particular characteristics, not individual animal use per individual culvert location. Our calculations were focused on frequency of use, not individual use. Also, many multiple cell culverts had different substrates and a few had different dimensions. We wanted to compare these differences rather than lose valuable data.

We compared seasonal and regional differences in capture rates among culverts by using ANOVA (Zar 1999) with post-hoc tests to determine which means were significantly different from each other (PASW Statistics v. 17.0.3 SPSS: An IBM Company). We used a multivariate method, Canonical Correspondence Analysis (CANOCO 4.5, Ithaca, New York), to elucidate the relationships between the biological assemblage of species captured by game cameras and their environment. We used ArcGIS 9.3 (ESRI© 1995–2010, Redlands, California) to determine the proportion of land use and land cover (LULC) types within a 0.62-mile (1 km) radius of each culvert site. We collected deer mortality data from the Large Animal Removal Reporting System (LARRS; State Highway Administration, Baltimore, Maryland). Observed categorical data were compared to expected species frequency with a χ^2 goodness-of-fit test (Fowler and Cohen 1990) (PASW Statistics v. 17.0.3 SPSS: An IBM Company). We used Anderson et al. (1976) to describe LULC characteristics.

RESULTS

We recorded 32,783 identifiable images (46.5% of the total number of images) of wildlife over 2.3 years. Forty species were recorded by camera traps (Table 6) and an additional 17 species were noted by direct visual observations (Table 7). We limited our statistical analysis to 12 species that had been recorded by camera traps in 30 or more culverts. Cartographic analysis was limited to the white-tailed deer.

Effect of Culvert Shape, Substrate Type, and Fence Arrangement

We used chi-square analysis to determine the association of the 12 major species with three categories: culvert shape, substrate type, and fence arrangement (Tables 3 and 4). Several species did not show any significant associations with these features. Northern raccoons (n = 246 culverts) did not use a given culvert shape (χ^2 = 0.015, 2 df, P = 0.992), substrate (χ^2 = 1.187, 5 df, P = 0.946), or fence arrangement (χ^2 = 0.355, 6 df, P = 0.999) more frequently than expected. Use by Virginia opossum (n = 129 culverts) also did not differ from the expected values for culvert shape (χ^2 = 5.845, 2 df, P = 0.054), substrate (χ^2 = 6.731, 5 df., P = 0.241), or fence arrangement (χ^2 = 1.292, 6 df, P = 0.972). Virginia opossum and northern raccoon were the only species documented at the four, type 6 fence sites, where one of the openings consisted of storm drain fields and street level drains. Use by woodchuck (n = 97 culverts) did not differ among culvert shapes (χ^2 = 0.994, 2 df, P = 0.608); the observed substrate type used by woodchuck also did not differ from the expected values (χ^2 = 3.601, 5 df, P = 0.608), nor did their use of different fence arrangements (χ^2 = 5.480, 5 df, P = 0.360). Humans (n = 66 culverts) showed no difference in frequency of use of different culvert shapes (χ^2 = 1.076, 2 df, P = 0.584), substrate types (χ^2 = 8.916, 5 df, P = 0.112), or fence arrangements (χ^2 = 9.557, 5 df, P = 0.089). Eastern gray squirrels (n = 53 culverts) were not found in any arch-shaped culverts, and did not show any affiliation for either box or cylinder shapes (χ^2 = 0.360, 1 df, P = 0.548). Eastern gray squirrels were not observed using any substrate more often than expected (χ^2 = 6.190, 5 df, P = 0.288). Eastern gray squirrels were not found in culverts with type 3 fence arrangements, i.e., culverts having fences ≥1.5 m tall forming a barrier between the culvert opening and the surrounding natural area on both sides. Use of culverts with the remaining fence arrangements were not significantly different from one another (χ^2 = 1.532, 4 df, P = 0.821). Norway rats (n = 52 culverts) did not use any culvert shape more or less than expected (χ^2 = 3.317, 2 df, P = 0.190); there were also no differences in use of culverts having different substrates (χ^2 = 4.883, 5 df, P = 0.430). Norway rats were not found in culverts having type 1 fences, i.e., culverts having fences ≥1.5 m tall existing between the road and the culvert opening so as to form a wildlife guide on both sides of the culvert. There was no significant difference in use of culverts with different fence types for Norway rat (χ^2 = 6.964, 4 df, P = 0.138). Common gray fox (n = 47 culverts) did not use any particular culvert shape more or less than expected by chance (χ^2 = 4.314, 2 df, P = 0.116). Use of culverts with different substrates by common gray fox was also not significantly different (χ^2 = 3.724, 5 df, P = 0.590). All fence arrangements at culverts used by common gray fox were used similarly (χ^2 = 8.824, 5 df, P = 0.116). White-footed or deer mice (n = 33 culverts) were not found in arch-shaped culverts. There was no significant difference in their use of box and cylinder-shaped culverts (χ^2 = 0.832, 1 df, P = 0.832). White-footed or deer mice were not recorded in culverts with cobble substrate. There was no difference among the remaining substrate types (χ^2 = 4.013, 4 df, P = 0.404). White-footed or deer mice were not documented to use culverts with three of the six possible fence arrangements, i.e., type 1, type 3, or type 4 (Table 4). Of the three remaining fence arrangements at culverts, there was no difference in use by white-footed or deer mouse (χ^2 = 0.656, 2 df, P = 0.720).

In contrast, some species showed greater use than expected of culverts with certain features. Domestic cats (n = 103 culverts) were found more frequently than expected using cylinder-shaped culverts (χ^2 = 7.869, 2 df, P = 0.020) and concrete substrate (χ^2 = 12.134, 5 df, P = 0.033), although there was no difference among fence arrangements (χ^2 = 0.703, 5 df, P = 0.983). The great blue heron (n = 77 culverts) used the box-shaped culverts more often than expected (χ^2 = 13.564, 2 df, P = 0.001). They also were found most often in culverts with sand substrate (χ^2 = 12.666, 5 df, P = 0.027). Fence arrangement did not affect culvert use by great blue heron (χ^2 = 5.052, 5 df, P = 0.410). Red fox (n = 66 culverts) was found in cylinder-shaped culverts most often (χ^2 = 9.930, 2 df, P = 0.007), but there was no difference in use of culverts with a particular substrate type (χ^2 = 10.738, 5 df, P = 0.057). They used culverts less frequently when fencing was absent on both sides of the culvert (χ^2 = 17.907, 5 df, P = 0.003). White-tailed deer (n = 63 culverts) were not strongly associated with a particular culvert shape (χ^2 = 5.589, 2 df, P = 0.061) or substrate type (χ^2 = 7.462, 5 df, P = 0.188); their use of culverts with no fence on either side of the highway was lower than at culverts with other fence arrangements (χ^2 = 26.491, 5 df, P < 0.001).

Seasonal and Regional Variation in Culvert Use

Northern raccoon, Virginia opossum, and white-tailed deer frequency of culvert use differed significantly among seasons; while all other sampled species showed no difference (Table 8). Spring and especially summer had the highest culvert use by northern raccoon. Fall culvert use by northern raccoon was quite variable. Winter had the lowest culvert use by Virginia opossum and was significantly lower than summer and fall. White-tailed deer had the highest use of culverts in summer, which was significantly higher than spring.

Mean frequency of culvert use by northern raccoon, Virginia opossum, domestic cat, red fox, white-tailed deer, and Norway rat differed significantly among regions (Table 9). Northern raccoon, red fox, white-tailed deer, and Norway rat used culverts in the Piedmont more frequently than in any other region. Virginia opossum and domestic cat used culverts most often in the Appalachian Mountain compared to other regions. We found common gray fox to be absent from culverts on the Eastern Shore.

Canonical Correspondence Analysis

Association with culvert structural variables

Canonical Correspondence Analysis (CCA) was used to elucidate the relationship between the 12 major camera-trapped species and the environmental and culvert structural variables. Twelve environmental and structural variables were used in the analyses (Figure 5).

A weighted correlation matrix described the relationship of the environmental and structural variables to the species and environmental axes. Axis 1 was correlated most strongly with culvert width ($r = 0.514$), and Axis 2 was most strongly correlated with culvert length ($r = -0.463$). The Monte Carlo permutation test (499 permutations) was significant ($P < 0.05$) for the first canonical axis and for all canonical axes (Table 10). Variance inflation factors (VIF) were between 1.06 and 2.95, indicating an acceptable or low multicollinearity among the environmental variables.

The four axes explained 16.4% of the variance in the 12 major culvert using species. The first and second axes explained 67.2% of the variation in the species-environment relationship (Table 11). The great blue heron was most closely associated with increasing average water depth and openness. Woodchuck, eastern gray squirrel, Norway rat, and white-footed or deer mouse were found in culverts with decreasing traffic volume, number of lanes, culvert length, distance to road, slope, and earth fill. Virginia opossum, domestic cat, woodchuck, and white-footed or deer mouse were also associated with culverts having decreasing height. Northern raccoons, occurring near the center of the two axes, were not associated with any particular variable; they were found in all types of culverts. The two largest species, humans and deer, were associated with increasing culvert width, height, and length; as well as with increasing traffic volume, number of lanes, slope, and earth fill. Both red and gray foxes used culverts characterized as longer, farther from the road, with greater traffic volume and number of lanes, and having steeper slopes, more earth fill above the culvert, less water, and being less open (Figure 5).

Association with Land Use/Land Cover

We also used CCA to associate the 12 most frequent camera-trap recorded species with LULC variables. Eleven LULC variables were used in the analyses (see legend for Figure 6).

A weighted correlation matrix described the relationship of the LULC variables to the species and environmental axes. Cultivated crops were correlated most strongly with Axis 1 ($r = -0.406$) and mixed forest was most strongly correlated with Axis 2 ($r = 0.255$). The Monte Carlo permutation test (499 permutations) was significant ($P < 0.05$) for the first canonical axis and for all canonical axes (Table 12). Variance inflation factors (VIF) were between 1.35 and 3.34, indicating a low multicollinearity among the selected LULC variables. Two variables, Developed Low Intensity and Developed Medium Intensity, were removed owing to issues of multicollinearity with the variable Developed High Intensity.

The four axes explained 7.5% of the variance in the 12 major culvert-using species. The first and second axes explained 51.6% of the variation in the species-environment relationship (Table 13). Northern raccoon, Virginia opossum, and domestic cat did not show a strong affiliation for any particular cover type at culvert sites used by them. Woodchuck and white-footed or deer mouse more frequently used culvert sites predominated by pasture, hay fields, and woody wetlands. Great blue herons frequently used culvert sites having more cultivated crops. Eastern gray squirrels used culverts surrounded by a greater extent of mixed and deciduous forests. Culvert use by Norway rat was greater in areas with more herbaceous wetlands. Red and common gray foxes used culverts located more often in areas that were highly developed and had more developed open areas and lawns. Humans used culverts most frequently in areas with developed lawns (Figure 6). Deer appeared to use culverts more often at sites surrounded by barren lands, i.e., without vegetation cover.

Comparison of Species and Structural Variables

We used a table of *t*-tests (Table 14) to compare the significance of variables at culverts that were used by a given species versus culverts that were not used by that species. We assessed the same 12 species and 12 variables analyzed by the first CCA. We did this in order to assign testable hypothetical values to these variables and also to confirm the results of the CCA.

Average depth of water was a significant variable for 11 of the 12 major species. Great blue heron was the only species that used culverts containing deeper water (Figure 7). All of the other species used culverts having shallower water than was found in culverts not used by these species (but, see Figure 8). Several of the culverts used by small mammals with maximum water depths greater than 20 cm also had ledges (Figure 9). In one case, a domestic cat was documented using a culvert with an average water depth of 82.5 cm, the water was frozen at the time.

Percent visibility, which is the portion of the entrance not obscured by vegetation, was significant for five of the 12 major species. Northern raccoon, domestic cat, and woodchuck used culverts that had more vegetation obscuring the entrance; whereas, great blue heron and humans used culverts having less vegetation obscuring the entrance (Figure 10). Only red fox used culverts having entrances closer to woody shrubs or trees that could serve as potential escape cover. Although other species demonstrated a similar use, none were statistically significant.

The difference in distances to the road bed at culverts used by a given species and those not used were significant for seven species. Woodchuck, great blue heron, and Norway rat occurred in culverts where the entrance was closer to the road bed. Red fox, humans, white-tailed deer, and gray fox used culverts where the entrance was farther from the road bed.

The degrees of slope from the top of the culvert to the edge of the paved surface were significantly different at culverts for six species. The slope at sites used by woodchuck, great blue heron, and Norway rat was less than the slope of the sites not used by these species; whereas, the slope of the sites used by red fox, gray fox, and white-tailed deer was greater than the slope at sites not used by these species.

The width of culverts used by Virginia opossum, domestic cat, red fox, and white-footed or deer mouse was narrower; in contrast, great blue heron, humans, and white-tailed deer used wider culverts (Figure 10). Culvert height differed significantly for five species; northern raccoon, great blue heron, eastern gray squirrel, humans, and white-tailed deer, all used taller culverts. Culvert length differed significantly for five species. Woodchucks and great blue heron occurred in shorter culverts; while, red and common gray fox, and white-tailed deer used longer culverts. Culvert openness (width × height / length) was significant for only two of the 12 species. Great blue heron used culverts that were more open. Red fox used culverts that were less open. Culvert openness was not a significant factor for white-tailed deer.

Earth fill is the height of soil between the top of the culvert entrance and the road bed. Woodchuck, great blue heron, and Norway rat used culverts with less earth fill, i.e., culverts closer to the height of the road bed. Red and common gray fox occurred in culverts with more earth fill.

The number of lanes differed significantly for three species. Great blue heron used culvert sites with fewer lanes of traffic. Red fox and deer used sites having more lanes of traffic. Traffic volume, the rate of daily traffic at the culvert site, differed significantly for five species. Woodchucks used culvert sites with less traffic volume. Red and common gray fox, humans, and white-tailed deer used culvert sites with greater traffic volume.

White-tailed Deer Activity

We examined the relationship between the monthly use of culvert sites by white-tailed deer, as documented by game cameras during this study, and white-tailed deer road-killed at those sites as documented by the Maryland State Highway Administration Large Animal Removal Reporting System (LARRS) during the same time period, i.e., 28 August 2008–3 January 2011. We counted locations as 236 combined culvert sites instead of the 265 individual culvert cells used for previous calculations. Multiple culvert cells at each site were combined and counted as one site. There were 143 of 236 sites associated with road-killed deer, and deer were detected by cameras at 59 of 236 sites (Figure 11). Deer road-kill was counted from 0.25 (0.40 km) miles in either direction along the road using the culvert site as a center point for a total 0.50 mile (0.80 km) stretch of road. The slope of the quadratic regression ($\hat{Y} = 1.984 - 17.870x + 38.337x^2$ [where x = deer road-kill rate]) was considered significant ($F_{[2, 233]} = 36.603$, $P \leq 0.001$). Although there was a positive relationship between the number of road-kills and use of culverts by white-tailed deer, the association was not very strong ($R^2 = 0.239$) (Figure 12).

We used the same criteria above to compare the deer road-killed at culvert sites where they had been detected by cameras ($n = 59$) to randomly-selected sites along the highway ($n = 64$). We found that culvert sites used by deer had a greater number of road-killed deer than were road-killed at the randomly-selected sites ($t_{[121]} = 2.523$, $P = 0.014$).

We used ArcGIS to plot locations of culverts used by white-tailed deer (Figure 13). The highest frequency of use by white-tailed deer occurred at culvert sites located in the Piedmont of central Maryland, particularly in Howard, Montgomery, and Frederick counties. There are about 100 culvert sites in the Piedmont; six of the eight culvert locations with type 1 fences in

Maryland, i.e., those that might function as a wildlife guide or funnel, occurred in the Piedmont. The lowest frequency of culvert use occurred at sites on the Eastern Shore, with white-tailed deer being found at only one site in the whole region.

Use of Culverts by Nesting Birds

We found two species of passerines that nested in culverts during the spring season. Barn swallow (*Hirundo rustica*) (Figure 14) and eastern phoebe (*Sayornis phoebe*) (Figure 15) made their adherent mud nests on the vertical walls inside of culverts. Box culverts were most frequently used for nest building by both barn swallow ($\chi^2 = 7.474$, 1 df, $P = 0.006$) and eastern phoebe ($\chi^2 = 18.292$, 1 df, $P < 0.001$). Neither species used arch culverts. On three occasions eastern phoebes used cameras or angle brackets as platforms for their nests inside of culverts.

Use of Culverts by Waterfowl

Mallard (*Anas platyrhynchos*), wood duck (*Aix sponsa*), and Canada goose (*Branta canadensis*) were all observed using culverts as family groups in the spring and early summer (Figure 16). Culverts are an integral part of the streams and waterways that waterfowl naturally frequent. An ANOVA showed no significant differences in seasonal frequency of waterfowl use of culverts ($F_{[3, 66]} = 2.534$, $P = 0.064$); but, most waterfowl occurrences in culverts happened in the spring ($n = 43$) compared to summer ($n = 10$), fall ($n = 5$), or winter ($n = 12$) during our 2.3-year survey.

Use of Culverts by Herpetofauna

Culverts were used by 19 species of herptiles (see Table 7). The common five-lined skink (*Plestiodon fasciatus*) seemed to use the concrete entrance for basking and foraging and did not appear to use the culvert for transit. Three species of aquatic turtles were found inside of culverts. We found three species of salamander in culverts. There were three species of snakes associated with culverts and eight species of frogs. The green frog (*Lithobates clamitans*) was the most commonly occurring herptile, often found in pools at the culvert openings. Our results show that many herptile species will use culverts for habitation as well as potentially for transit.

DISCUSSION

Few studies have investigated wildlife use of culverts across such a broad geographic region, from the Appalachian Mountains to the Piedmont and Coastal Plain of Maryland, or by such a broad spectrum of wildlife species. Every county in Maryland was represented in our sample. Our study confirms that many wildlife species use road drainage structures to cross roads. We detected 57 species that used 265 culverts to cross roads or for habitation in Maryland. This number of species and number of surveilled culverts are the largest reported in the literature (Foster and Humphrey 1995, Yanes et al. 1995, Clevenger and Waltho 2000, Ng et al. 2001, Clevenger et al. 2001*a*, Brudin 2003, Gordon and Anderson 2003, Donaldson 2005, Rogers et al. 2009).

Seasonal Variation in Culvert Use

Culvert use by certain species did vary on a seasonal basis. For northern raccoons, the highest frequency of use of culverts occurred in the summer. This could be due to mother and offspring family groups being formed and traveling together at this time (Lotze and Anderson 1979). Virginia opossum traveled through culverts more frequently in the summer and fall. Virginia opossum were only observed traveling as solitary individuals, though females may have been carrying offspring. Both northern raccoon (Stuewer 1943) and Virginia opossum (Kanda et al. 2005) den during particularly cold winter weather. Denning restricts travel thereby reducing the use of culverts by these species during the winter season. Deer are also more restricted in their foraging during winter, especially due to snow fall of even slight depths (Beier and McCullough 1990). We found that deer used culverts most in the summer and fall and least in the winter and spring.

Regional Variation in Culvert Use

Northern raccoon used culverts most frequently in the Piedmont region. This result was in contrast to Sonenshine and Winslow (1972), who found higher capture rates in the Coastal Plain compared to the Piedmont of Virginia. Northern raccoon populations fluctuate significantly over multiple years (Lotze and Anderson 1979), being affected by several epidemic diseases, among them rabies and canine distemper (Johnson 1970). There were no known disease outbreaks among raccoons during our study (Cindy Driscoll, MDDNR, personal communication). Northern raccoon populations can be higher in more urbanized habitats (Prange et al. 2003). According to Hoffman and Gottschang (1977), suburban areas provide excellent habitat for northern raccoons. The Piedmont region is largely mixed urban, suburban, and rural in character; this may contribute to higher northern raccoon density in this region.

Virginia opossum used culverts in the Appalachian Mountain region more frequently than in the other three regions. While Virginia opossum are known to inhabit a wide variety of habitats (McManus 1974), they tend to stay near water (Llewellyn and Dale 1964). Perhaps the topography of the Appalachian Mountain region encourages Virginia opossum to utilize culverts more frequently than in regions with less topographic relief. However, Kanda et al. (2006) found road-killed Virginia opossum in low elevation areas associated with human habitation in central Massachusetts. Alternately, there may be some undiscovered reason for higher use of culverts by Virginia opossum in the Appalachian Mountain region.

Domestic cats also used culverts in the primarily rural Appalachian Mountain region more frequently. According to Schmidt et al. (2007), human interaction, such as feeding, may concentrate feral cats in certain localities resulting in feral cat colonies. Warner (1985) found that free-roaming cats concentrate around farmsteads. Centonze and Levy (2002) reported that most (69%) feral cat colonies in north-central Florida occurred in rural areas or small towns, whereas a national survey by Clifton (1992) found that only 20% of feral cats occurred in rural areas. Our data contribute to the poorly understood regional distribution of free-roaming and feral cats.

The red fox is the most widely distributed carnivore in the world (Larivière and Pasitschniak-Arts 1996). We found that the red fox used culverts more frequently in the Piedmont region. Harris and Rayner (1986) found red fox to be more common in residential suburban areas of England. Randa and Yunger (2006) located foxes in forest interior, shrublands, and old fields. The Piedmont region has a good mix of urban, suburban, and rural habitats.

White-tailed deer also used culverts more frequently in the Piedmont region, which is characterized by urban centers and farmland. White-tailed deer benefit from anthropogenically-altered landscapes, such as second-growth forests and farmlands (Smith 1991). Culverts in the Appalachian Mountain region were among the least used by deer. This occurrence may be due in part to the more abundant forests in the Appalachian Mountain region. Forested landscapes may allow for more alternative avenues for deer to cross highways. In contrast, forested riparian habitats in the more anthropogenically-modified landscapes in the rest of the state may guide more deer into culverts (Smith 1991).

Norway rats used culverts more frequently in the Piedmont region. Norway rats are ubiquitous, found worldwide on every continent except Antarctica, and typically associated with urban areas (Scientific-web.com 2011). The difference among mean rate of culvert use per region, while statistically significant, is so slight as to be nearly negligible. There may be no biologically meaningful reason for the small difference among regional use of culverts by Norway rat.

Predator Avoidance in Culverts

We did not find any evidence of native large predator species using culverts; black bear (*Ursus americanus*), bobcat (*Lynx rufus*), and coyote (*Canis latrans*) were all absent from surveyed culverts. Domestic dogs (*Canis familiaris*) were present in 19 culverts, four of these were also used by white-tailed deer (21%), indicating that use of culverts by domestic dogs did not deter white-tailed deer.

There was anecdotal evidence that black bear have used other culverts in Garrett and Allegany counties (Rich Zeger, SHA, personal communication). Both Brudin (2003) and Donaldson (2005) reported culvert use by black bear in the Mid-Atlantic States. Clevenger and Waltho (2000) found an inverse relationship between predator and prey use of culverts in Canada. The lack of major predators in our survey suggests that predator avoidance may not play an important role in culvert selection by white-tailed deer and other potential prey species in Maryland.

Clevenger and Waltho (2000) suggested that human activity may preclude wildlife use of culverts. We found no significant relationships between human use of culverts and use of culverts by the other 11 major species. Nineteen of 66 culverts (29%) used by humans were also used by deer, several of them heavily so. Based on this, we believe that our placement and retrieval of cameras probably had little effect on white-tailed deer use of culverts. Species in our survey were, therefore, more likely to select culverts based on structural and habitat variables rather than predator or human avoidance.

Influence of Average Water Depth and Use of Ledges

Average depth of water was a significant variable for 11 of the 12 major species we sampled. Brudin (2003) also found water level to be an obstruction for deer and other mammal species. Since high water level is apparently a deterrent to most of the species in the sampled culverts, we recommend the construction of ledges, particularly for small- and medium-sized mammals. We found that small mammals used existing ledges to possibly avoid water in our survey. Meaney et al. (2007) found that retrofitting a culvert with ledges was an important part of habitat mitigation for the endangered Preble's meadow jumping mouse (*Zapus hudsonius preblei*) in Colorado. AZGFD (2006) also recommended using ledges or shelves to encourage the passage of small and medium-sized mammals. Larger ledges, or room for dry land on either side of a stream, may also be useful in coaxing larger wildlife species through culverts with deep water (AZGFD 2006).

Landscaping at the Culvert Entrance

The amount of cover present at a culvert opening is considered to be important for various species, particularly small mammals and mesofauna (Rodriguez et al. 1996, Clevenger et al. 2001*a*). Vegetative cover is believed to offer protection and provide a sense of security to certain animals approaching a culvert (Rodriguez et al. 1996, Clevenger et al. 2001*a*, AZGFD 2006). Northern raccoon, domestic cat, and woodchuck used culverts more often if vegetative cover at the entrance was greater.

Vegetative cover at a culvert entrance can also obscure visibility through the culvert and leave prey species more vulnerable to predators. We found that different species reacted differently to vegetation at the entrance. Not all species were attracted to vegetative cover obscuring the entrance, some, like humans and great blue herons, appeared to be deterred by such conditions. Ungulates, in particular, may be more likely to cross through a culvert with a clear view to the other side (AZDGF 2006).

Nearness to woody cover was found to be a significant variable only for red fox. Proximity to woody cover is generally believed to positively influence wildlife use of underpasses and culverts, particularly for carnivores (Rodriguez et al. 1996, Clevenger et al. 2001*a*). The landscaping of vegetation immediately surrounding the culvert entrance was less important than the structural variables of the surveyed culverts for most species, with the exception of red fox.

The Effect of Land Use and Land Cover

We used a 1 km (0.62 miles) radius circle to describe LULC surrounding each culvert. Certain aspects of LULC did appear to be important to species use of culverts. Cultivated crop land and mixed forest land most completely described Axis 1 and Axis 2 of the CCA, respectively.

Red and gray fox, and humans, were associated with lawns. Red and gray fox are known to inhabit urban areas (Larivière and Pasitschniak-Arts 1996, Riley 2006, Gosselink et al. 2007).

Virginia opossum and domestic cat used culverts near deciduous forests and open water. Virginia opossum are known to be affiliated with waterways and riparian forests (Llewellyn and Dale 1964, McManus 1974). White-tailed deer use of culverts was associated with barren land lacking vegetation. White-tailed deer are more likely to be found in forested riparian zones in less forested habitats (Smith 1991), perhaps resulting in greater culvert use in those areas.

Use of Culverts by White-tailed Deer

We found that white-tailed deer will use culverts smaller than those that have been documented by previous studies. Reed et al. (1975) suggested that 4.27 m was a minimum width and height dimension for mule deer (*Odocoileus hemionus*) in Colorado. Gordon and Anderson (2003) suggested that minimum dimensions for mule deer be 6.1 m wide and 2.44 m tall in Wyoming. Brudin (2003) surveyed nine box culverts that had been used by white-tailed deer (*Odocoileus virginianus*) in Pennsylvania with average dimensions of 4.6 m wide by 2.5 m tall. Our study found that white-tailed deer can use culverts as small as 1.42 m wide and 0.99 m tall. This culvert was half filled with sediment and was used, to our knowledge, only once by a juvenile deer. Average width and height of culverts used by white-tailed deer in this study were 2.99 m and 2.24 m, respectively. According to Bisonette and Cramer (2008), ungulates will use smaller culverts in urban and suburban settings. Gates (1993) reported that deer that were highly motivated to cross a highway will use smaller culverts than deer less motivated. Clevenger and Waltho (2005) found that mule deer and elk used narrow crossing structures with long dimensions and low openness ratios in Banff National Park, Canada, to cross the Trans-Canada Highway. Openness did not seem to be as important as width for the passage of white-tailed deer in our study. Our results suggest that white-tailed deer will use longer culverts with lower openness indices provided they are wide enough and tall enough to allow white-tailed deer to pass unimpeded.

Research indicates that an unobstructed view of the far side of a culvert is an important factor influencing an animal's use of a culvert (Foster and Humphrey 1995, AZGFD 2006). We found that 50 culverts (79%) used by white-tailed deer had an 80% or better unobstructed view of the far side. On two occasions, research team member, James L. Sparks, Jr., was in the culvert when deer approached. On one of these times, a doe and two yearlings approached, but did not enter the culvert. On the other occasion, the deer entered and came within a few meters as Sparks stood motionless in the center of the arch culvert. During both of these events, the deer moved their heads from side to side appearing to scan the sides of the culverts. Visual continuity through the culvert may be an important variable to be considered in culvert construction. AZGFD (2006) recommended keeping the culvert entrance clear of vegetation when planning for deer to use culverts.

We documented 72 occasions of doe leading young through culverts. Deer often travel in matriarchal family groups (Smith 1991). Such behavior would familiarize offspring with passageways provided by culverts.

Although the relationship between road-kills near culverts and use by white-tailed deer was positive, the quadratic curve that best fit this relationship was driven by a couple of factors. Culverts receiving no use by deer were in areas of low numbers of road-kills; plus the one site with the highest number of road-kills also had the highest number of deer using culverts. Taking these factors into consideration, deer use of culverts may actually have a lowering effect on road-kills. More research is needed to tease apart this relationship. We did find that culvert sites used by deer had a higher incidence of road-kills than random sites, indicating that riparian forests may concentrate deer activity (Smith 1991, Naiman and Décamps 1997, Whittaker and Lindzey 2004). Permanent protection and restoration of riparian forests for the benefit of wildlife and reduction of sediments and nutrients entering streams are encouraged by the U.S. Department of Agriculture under the Conservation Reserve Program or CRP (http://www.md.nrcs.usda.gov/programs/crp_crep/crp_crep.html, accessed July 28, 2011); thereby providing water and cover, as well as wildlife passage to stream culverts.

Use of Culverts by Northern Raccoon

Northern raccoons are prolific, highly adaptable omnivores (Lotze and Anderson 1979). Randa and Yunger (2006) found northern raccoon to inhabit all types of habitats across an urban-rural gradient in Illinois. Northern raccoons were the most frequently photographed species in our survey, using all types of culverts. Gates (1993) in eastern Maryland, Brudin (2003) in central Pennsylvania, Wolf et al. (2003) in northern Virginia, and Ng et al. (2004) in southern California, likewise found that northern raccoons were predominant in their studies of wildlife use of culverts.

Northern raccoons have the propensity to utilize culverts frequently (Foster and Humphrey 1995, Brudin 2003, Wolf et al. 2003, Ng et al. 2003). Terrestrial species that use culverts to cross roads regularly probably suffer less from the deleterious effects of habitat fragmentation than do those species that do not use culverts to cross roads (Yanes et al. 1995, Ng et al. 2001, Forman et al. 2003). Existing drainage culverts with minimum useable structural dimensions already improve survivability of species that frequent riparian corridors.

Use of Culverts by Great Blue Heron

Great blue herons used culverts near cultivated crops. Dowd and Flake (1985) found that great blue herons in South Dakota used pasture and cultivated land to forage for small mammals and amphibians. However, Gibbs and Kinkel (1997) found that great blue heron nesting colonies in Illinois were less associated with agriculture. Our observations were not limited to the breeding season or breeding colonies. Great blue heron were most closely associated with increasing average water depth and openness. Great blue herons undoubtedly forage for small fish, amphibians, and a variety of aquatic invertebrates in culverts and require room to accommodate their up to 6 foot (1.8 m) wing span should an immediate escape become necessary.

Use of Culverts as Mitigation for Herpetofauna

Roads have a severe impact on many species of herpetofauna (Andrews et al. 2008). Mitigation measures include building drift fences to enhance the use of existing culverts by herptiles in Florida (Dockstader and Southall 2003, Aresco 2005) and building small dry culverts with drift fences for box turtles in Maryland (Hagood 2009). While culverts with drift fences have been built specifically for eastern box turtles (*Terrapene carolina*) in Maryland (Hagood 2009), we found no box turtles in our drainage structures. We did find aquatic species; snapping turtles (*Chelydra serpentina*), red-eared sliders (*Trachemys scripta elegans*), and painted turtles (*Chrysemys picta*). Ward et al. (2008) found that culverts could be useful in linking salamander stream habitat in West Virginia. We found red-backed (*Plethodon cinereus*), northern dusky (*Desmognathus fuscus*), and two-lined (*Eurycea bislineata*) salamanders. Culverts can be a valuable part of herpetofauna conservation, but their employment requires the use of drift fences, or other types of funnels, to be effective (Bird 2003, Dockstader and Southall 2003, Aresco 2005, Hagood 2009).

CONCLUSIONS

The earliest documented use of a dedicated wildlife passage was in Florida in the 1950s (Forman et al. 2003). Since then there has been renewed interest in mitigation of wildlife road mortality by way of existing culverts (Foster and Humphrey 1995, Yanes et al. 1995, Rodriguez et al. 1996, Clevenger and Waltho 2000, Clevenger et al. 2001*a*, Forman et al. 2003, Ng et al. 2004, Aresco 2005, Grilo et al. 2008, Cramer and Leavitt 2009, Seiler and Olsson 2009). The number one research priority in road ecology, according to Bisonette and Cramer (2008), is to develop an understanding of what constitutes an effective mitigation structure. Our study included a large sample of existing culverts in the Mid-Atlantic region, creating an improved concept of functional wildlife crossing sites.

We have demonstrated that existing culverts improve habitat permeability or connectivity for a number of diverse species. Proper dimensions of culverts to accommodate target species, such as white-tailed deer, can be determined more accurately from our large sample of culverts. While it seems that placement of culverts along waterways was effective for many white-tailed deer, orientation at road-kill hot spots may further mitigate deer-vehicle collisions. Effective use of fencing may also greatly improve culvert use by deer (Ward 1982, Gates 1993, Clevenger et al. 2001*b*). Use of fencing without underpasses may do little more than concentrate deer-vehicle collisions into unfenced or compromised areas (Feldhamer et al. 1986). Conversely, combined use of appropriate underpasses and well-maintained deer fencing may greatly reduce deer collisions (Clevenger et al. 2001*b*, McCollister and Van Manen 2010).

Alternately, or perhaps complementary to fencing, allometrically-scaled wildlife crossings may be used to improve wildlife movements (Bisonette and Cramer 2008). Allometrically-scaled wildlife crossings are suitable crossings that are placed at distances reflecting the home range size of the target species. A combination of the above mentioned techniques may substantially reduce road-kill related accidents in the State of Maryland.

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LITERATURE CITED

Allen, R. E., and D. R. McCullough. 1976. Deer-car accidents in southern Michigan. Journal of Wildlife Management 40:317–325.

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. U.S. Geological Survey Professional Paper 964. U.S. Geological Survey, Washington, D.C., USA.

Andrews, K. M., J. W. Gibbons, and D. M. Jochimsen. 2008. Ecological effects of roads on amphibians and reptiles: a literature review. Pages 121–143 *in* Urban herpetology. J. C. Mitchell, R. E. Jung Brown, and B. Bartholomew, editors. Society for the Study of Amphibians and Reptiles (SSAR), Salt Lake City, Utah.

Aresco, M. J. 2005. Mitigation measures to reduce highway mortality of turtles and other herpetofauna at a north Florida lake. Journal of Wildlife Management 69:549–560.

Arizona Game and Fish Department [AZGFD]. 2006. Guidelines for culvert construction to accommodate fish and wildlife movement and passage. Arizona Game and Fish Department, Habitat Branch, Phoenix, Arizona, USA. <http://www.azgfd.gov/hgis/pdfs/CulvertGuidelinesforWildlifeCrossings.pdf>. Accessed 13 Oct 2010.

Ascensão, F., and A. Mira. 2007. Factors affecting culvert use by vertebrates along two stretches of road in southern Portugal. Ecological Research 22:57–66.

Bashore, T. L., W. M. Tzilkowski, and E. D. Bellis. 1985. Analysis of deer-vehicle collision sites in Pennsylvania. Journal of Wildlife Management 49:769–774.

Beier, P., and D. R. McCullogh. 1990. Factors influencing white-tailed deer activity patterns and habitat use. Wildlife Monographs 109:3–51.

Bellis, E. D., and H. B. Graves. 1971. Deer mortality on a Pennsylvania interstate highway. Journal of Wildlife Management 35:232–237.

Bird, R. 2003. Improving a culvert keeps turtles on the wetland—and off the road. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., USA. <http://www.fhwa.dot.gov/environment/wildlifeprotection/index.cfm?fuseaction=home.viewArticle&articleID=99>. Accessed 13 Oct 2010.

Bisonette, J. A., and P. C. Cramer. 2008. Evaluation of the use and effectiveness of wildlife crossings. National Cooperative Highway Research Program Report 615. National Academy of Sciences, Transportation Research Board, Washington, D.C., USA.

Braun, E. L. 1950. Deciduous forests of eastern North America. Blackiston Company, Philadelphia, Pennsylvania, USA.

Brudin, C. O. 2003. Wildlife use of existing culverts and bridges in north central Pennsylvania. Pages 344–352 *in* Proceedings of the 2003 International Conference on Ecology and Transportation. C. L. Irwin, P. Garrett, and K. P. McDermott, editors. Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina.

Centonze, L. A., and J. K. Levy. 2002. Characteristics of free roaming cats and their care takers. Journal of the American Veterinary Medical Association 220:1627–1633.

CityData.com. 2010. Maryland climate. <http://www.city-data.com/states/Maryland-Climate.html>. Accessed 13 Oct 2010.

Clevenger, A. P., B. Chruszcz, and K. Gunson. 2001*a*. Drainage culverts as habitat linkages and factors affecting passage by mammals. Journal of Applied Ecology 38:1340–1349.

Clevenger, A. P., B. Chruszcz, and K. Gunson. 2001*b*. Highway mitigation fencing reduces wildlife vehicle collisions. Wildlife Society Bulletin 29:646–653.

Clevenger, A. P., and N. Waltho. 2000. Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada. Conservation Biology 14:47–56.

Clevenger, A. P., and N. Waltho. 2005. Performance indices to identify attributes of highway crossing structures facilitating movement of large mammals. Biological Conservation 121:453–464.

Clifton, M. 1992. Seeking the truth about feral cats and the people who help them. Animal People November 1:7–10.

Conover, M. R., W. C. Pitt, K. K. Kessler, T. J. DuBow, and W. A. Sanborn. 1995. Review of human injuries, illnesses, and economic losses caused by wildlife in the United States. Wildlife Society Bulletin 23:407–414.

Cramer, P. C., and S. Leavitt. 2009. Right of way: giving animals safe passage across roadways. Wildlife Professional 3:56–60.

Donaldson, B. M. 2005. Use of highway underpasses by large mammals and other wildlife in Virginia and factors influencing their effectiveness. Pages 433–441 *in* 2005 Proceedings of the International Conference on Ecology and Transportation. C. L. Irwin, P. Garrett,

K. P. McDermott, editors. Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina.

Dockstader, J. D., and P. D. Southall. 2003. Ecopassage reduces roadkills: barrier and underpass in Florida preserve animal lives. Transportation Research Board, Washington, D.C. TR News 227:38–39

Dowd, E. M., and L. D. Flake. 1985. Foraging habitats and movements of nesting great blue herons in a prairie river ecosystem, South Dakota. Journal of Field Ornithology 56:379–387.

Feldhamer, G. A., J. E. Gates, D. M. Harman, A. J. Loranger, and K. R. Dixon. 1986. Effects of interstate highway fencing on white-tailed deer activity. Journal of Wildlife Management 50:497–503.

Forman, R. T. T., and L. E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29:207–232.

Forman, R. T. T., D. Sperling, J. A. Bisonette, A. P. Clevenger, C. D. Cutshall, V. H. Dale, L. Fahrig, R. France, C. R. Goldman, K. Heanue, J. A. Jones, F. J. Swanson, T. Turentine, and C. Winter. 2003. Road ecology: science and solutions. Island Press, Washington, D.C., USA.

Ford, A.T., A. P. Clevenger, and A. Bennett. 2009. Comparison of methods of monitoring crossing structures on highways. Journal of Wildlife Management 73:1213–1222.

Foster, M. L., and S. R. Humphrey. 1995. Use of highway underpasses by Florida panthers and other wildlife. Wildlife Society Bulletin 23:95–100.

Fowler, J., and L. Cohen. 1990. Practical statistics for field biology. John Wiley and Sons, New York, New York, USA.

Gates, W. R. 1993. Mammalian use of over-sized stream culverts under Interstate 97, Anne Arundel County, Maryland. M.S. thesis. Frostburg State University, Frostburg, Maryland, USA.

Gibbs, J. P., and L. K. Kinkel. 1997. Determinants of the size and location of great blue heron colonies. Colonial Waterbirds 20:1–7

Gompper, M. E., R. W. Kays, J. C. Ray, S. D. LaPoint, D. A. Bogan, and J. R. Cryan. 2006. A comparison of non-invasive techniques to survey carnivore communities in northeastern North America. Wildlife Society Bulletin 34:1142–1151.

Gordon, K. M., and S. H. Anderson. 2003. Mule deer use of underpasses in western and southeastern Wyoming. Pages 309–318 *in* 2003 Proceedings of the International Conference on Ecology and Transportation. C. L. Irwin, P. Garrett, and K. P.

McDermott, editors. Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina.

Gosselink, T. E., T. R. van Deelen, R. E. Warner, and P. C. Mankin. 2007. Survival and cause specific mortality of red foxes in agricultural and urban areas of Illinois. Journal of Wildlife Management 71:1862–1873.

Grilo, C., J. A. Bisonette, and M. Santos-Reis. 2008. Response of carnivores to existing highway culverts and underpasses: implications for road planning and mitigation. Biodiversity and Conservation 17:1685–1699.

Hagood, S. 2009. How did the box turtle cross the road? With a wildlife crossing. Humane Society of the United States, Washington, D.C., USA. <http://www.humanesociety.org/issues/wildlife_roads/facts/box_turtle_road.html>. Accessed 13 Oct 2010.

Hardy, A., A. P. Clevenger, M. Huijser, and N. Graham. 2003. An overview of methods and approaches for evaluating the effectiveness of wildlife crossing structures: emphasizing the science in applied science. Pages 319–330 *in* Proceedings of the International Conference on Ecology and Transportation. C. L. Irwin, P. Garrett, and K. P. McDermott editors. Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina.

Harris, S., and J. M. V. Rayner. 1986. Urban fox (*Vulpes vulpes*) population estimates and habitat requirements in several British cities. Journal of Animal Ecology 55:575–591.

Hoffman, C. O., and J. L. Gottschang. 1977. Numbers, distribution, and movements of a raccoon population in a suburban residential community. Journal of Mammalogy 58:623–636.

Hubbard, M. W., B. J. Danielson, and R. A. Schmitz. 2000. Factors influencing the location of deer vehicle accidents in Iowa. Journal of Wildlife Management 64:707–713.

Kanda, L. L., T. K. Fuller, and K. D. Friedland. 2005. Temperature sensor evaluation of opossum winter activity. Wildlife Society Bulletin 33:1425–1431.

Kanda, L. L., T. K. Fuller, and P. R. Sievert. 2006. Landscape association of road-killed Virginia opossums (*Didelphis virginiana*) in central Massachusetts. American Midland Naturalist 156:128–134.

Johnson, A. S. 1970. Biology of the raccoon (*Procyon lotor varius* Nelson and Goldman) in Alabama. Auburn University, Alabama Agricultural Experiment Station, Auburn, Alabama. Bulletin 402:1–148.

Larivière, S., and M. Pasitschniak-Arts. 1996. *Vulpes vulpes*. Mammalian Species 537:1–11.

Llewellyn, L. M., and F. H. Dale. 1964. Notes on the ecology of the opossum in Maryland. Journal of Mammalogy 45:113–122.

Lotze, J. H., and S. Anderson. 1979. *Procyon lotor*. Mammalian Species 119:1–8.

Maryland State Highway Administration [SHA]. 2003. Guide for completing structure inventory and appraisal input forms. Maryland State Highway Administration, Office of Bridge Development, Baltimore, Maryland, USA.

Malo, J. E., F. Suarez, and A. Diaz. 2004. Can we mitigate animal-vehicle accidents using predictive models? Journal of Applied Ecology 41:701–710.

McManus, J. J. 1974. *Didelphis virginiana*. Mammalian Species 40:1–6

McCollister, M. F., and F. T. van Manen. 2010. Effectiveness of wildlife underpasses and fencing to reduce wildlife collisions. Journal of Wildlife Management 74:1722–1733

Meaney, C., M. Bakeman, M. Reed-Eckert, and E. Wostl. 2007. Effectiveness of ledges in culverts for small mammal passage. Report No. C-DOT-2007-9. Colorado Department of Transportation, Research Branch, Denver, Colorado, USA.

Naiman, R. J., and H. Décamps. 1997. The ecology of interfaces: riparian zones. Annual Review of Ecology and Systematics. 28:621–658.

NationalAtlas.gov. 2010. Annual precipitation in the State of Maryland. U.S. Department of the Interior and U.S. Geological Survey, Washington, D.C., USA. <www.nationalatlas.gov/printable/images/pdf/precip/pageprecip_md3.pdf>. Accessed 13 Oct 2010.

Ng, S., J. W. Dole, R. M. Sauvajot, S. P. D. Riley, and T. J. Valone. 2004. Use of highway undercrossing by wildlife in southern California. Biological Conservation 115:499–507.

Office of Highway Policy Information [OHPI]. 2007. Highway statistics 2007. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., USA. <http://www.fhwa.dot.gov/policyinformation/statistics/2007/>. Accessed 22 Jun 2011.

Paradiso, J. L. 1969. Mammals of Maryland. North American Fauna 66. U.S. Bureau of Sport Fisheries and Wildlife, Washington, D.C., USA.

Prange, S., S. D. Gehrt, and E. P. Wiggers. 2003. Demographic factors contributing to high raccoon densities in urban landscapes. Journal of Wildlife Management 67:224–333.

Puglisi, M. J., J. S. Lindzey, and E. D. Bellis. 1974. Factors associated with highway mortality of white-tailed deer. Journal of Wildlife Management 38:799–807.

Randa, L. A., and J. A. Yunger. 2006. Carnivore occurrence along an urban-rural gradient: a landscape level analysis. Journal of Wildlife Management 87:1154–1164.

Reed, D. F., T. N. Woodard, and T. M. Pojar. 1975. Behavioral response of mule deer to a highway underpass. Journal of Wildlife Management 39:361–367.

Riley, S. P. D. 2006. Spatial ecology of bobcats and gray foxes in urban and rural zones of a national park. Journal of Wildlife Management 70:1425–1435.

Rodriguez, R., G. Crema, and M. Delibes. 1996. Use of non-wildlife passages across a high speed railway by terrestrial vertebrates. Journal of Applied Ecology 33:1527–1540.

Rogers, L., D. Stimson, K. Holden, D. Kay, D. Kaye, R. McAdow, B. Metcalfe, B. Windmiller, and N. Charney. 2009. Wildlife tunnels under a busy suburban Boston roadway. Pages 102–115 *in* 2009 Proceedings of the International Conference on Ecology and Transportation. P. J. Wagner, D. Nelson, and E. Murray, editors. Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina.

Romin, L. A., and J. A. Bisonette. 1996. Deer vehicle collisions: status of state monitoring activities and mitigation efforts. Wildlife Society Bulletin 24:276–283.

Schmidt, P. M., R. R. Lopez, and B. A. Collier. 2007. Survival, fecundity, and movements of free roaming cats. Journal of Wildlife Management 71:915–919.

Schwabe, K. A., and P. W. Schumann. 2002. Deer vehicle collisions and deer value: an analysis of competing literatures. Wildlife Society Bulletin 30:609–615.

Scientific-web.com. 2011. *Rattus norvegicus.* <http://www.scientific-web.com/en/Biology/Animalia/Chordata/Mammalia/RattusNorvegicus01.html> Accessed 28 Apr 2011.

Seiler, A., and M. Olsson. 2009. Are non-wildlife underpasses effective passages for wildlife. Pages 317–331 *in* 2009 Proceedings of the International Conference on Ecology and Transportation. P. J. Wagner, D. Nelson, and E. Murray, editors. Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina.

Smith, D. J. 2003. Monitoring wildlife use and determining standards for culvert design. Final report presented to the Florida Department of Transportation for contract BC354-34. University of Florida, Department of Wildlife Ecology and Conservation, Gainesville, Florida.

Smith, W. P. 1991. *Odocoileus virginianus*. Mammalian Species 388:1–13.

Sonenshine, D. E., and E. L. Winslow. 1972. Contrasts in distribution of raccoons in two Virginia localities. Journal of Wildlife Management 36:838–847.

Spellerberg, I. F. 1998. Ecological effects of roads and traffic: a literature review. Global Biology and Biogeography Letters 7:317–333.

Stall, C. 1989. Animal tracks of the Mid-Atlantic States: District of Columbia, New York, New Jersey, Pennsylvania, Delaware, Maryland, Virginia and West Virginia. The Mountaineers, Seattle, Washington, USA.

Stewart, R. E., and C. S. Robbins. 1958. Birds of Maryland and the District of Columbia. North American Fauna 62. U.S. Bureau of Sport Fisheries and Wildlife, Washington, D.C., USA.

Stuewer, F. W. 1943. Raccoons: their habits and managements in Michigan. Ecological Monographs 13:203–257.

Trombulak, S. C., and C. A. Frissel. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14:18–30.

U.S. Census Bureau [USCB]. 2010. State and county quick facts: Maryland. U.S. Census Bureau, Washington, D.C., USA. <http://quickfacts.census.gov/qfd/states/24000.html>. Accessed 13 Oct 2010.

Ward, A. L. 1982. Mule deer behavior in relation to fencing and underpasses on Interstate 80 in Wyoming. Transportation Research Record 859:8–13.

Ward, R. L., J. T. Anderson, and J. T. Petty. 2008. Effects of road crossings on stream and streamside salamanders. Journal of Wildlife Management 72:760–771.

Warner, R. E. 1985. Demography and movements of free-ranging domestic cats in rural Illinois. Journal of Wildlife Management 49:340–346.

Watson, M. L. 2005. Habitat fragmentation and the effects of roads on wildlife and habitats: background and literature review. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Whittaker, D. G., and F. G. Lindzey. 2004. Habitat use patterns of sympatric deer species on Rocky Mountain Arsenal, Colorado. Wildlife Society Bulletin. 32:1114–1123.

Wolf, K. N., F. Elvinger, and J. L. Pilcicki. 2003. Infrared triggered photography and tracking plates to monitor oral rabies vaccine bait contact by raccoons in culverts. Wildlife Society Bulletin 31:387–391.

Yanes, M., J. M. Velasco, and F. Suarez. 1995. Permeability of roads and railways to vertebrates: the importance of culverts. Biological Conservation 71:217–222.

Zar, J. H. 1999. Biostatistical analysis. Fourth edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

Table 1. Camera effort per biotic region or physiographic province in Maryland.

	Camera/mile^2 × 100
Eastern Shore	0.010217
Western Shore	0.034906
Piedmont	0.036439
Appalachian Mountain	0.035108

Table 2. Summary of sites with camera activity during the course of this 2.3-year study in Maryland.

Descriptor	No. cameras
Total original sites	316
Cameras stolen or flooded during first placement	−3
Sites never found	−48
Total cells visited at least once	265
Removed because of theft or vandalism	−18
Removed because of flooding	−14
Removed for other reasons	−5
Total cells removed during study	37
Final count of continuously active cells for all nine sampling cycles	228

Table 3. Shapes and associated substrates of culverts surveyed throughout Maryland.

Shape	Substrate						Total
	Silt	Sand	Gravel	Cobble	Steel	Concrete	
Arch	5	3	7	2	0	3	20
Box	17	14	20	8	0	42	101
Cylinder	23	18	13	10	35	45	144
Total	45	35	40	20	35	90	265

Table 4. Descriptions of fence arrangements for each culvert cell encountered during this study in Maryland.

Type	Description	No.	Percent
1	Sites with both sides having a fence ≥1.5 m tall, the fence being the same or lesser distance from the road as the culvert opening, thereby forming a wildlife guide or funnel.	10	4
2	Sites with one side having a fence ≥1.5 m tall, the fence being the same or lesser distance from the road as the culvert opening, thereby forming a wildlife guide or funnel.	19	7
3	Sites with both sides having a fence ≥1.5 m tall, both fences being at greater distances from the road to the culvert opening, thereby forming a potential barrier.	6	2
4	Sites with one side having a fence ≥1.5 m tall, that fence being a greater distance from the road to the culvert opening, thereby forming a potential barrier.	21	8
5	Sites with one or both sides having a fence <1.5 m or taller, or otherwise of a type not considered to hinder or direct wildlife toward the culvert opening	12	4
6	Sites associated with street level storm drain fields at one opening.	5	2
7	Sites with no fences.	192	73
Total		265	100

Table 5. Continuous variables used to analyze species relationships to physical parameters of culverts in Maryland (*n* = 265).

	Variables measured by authors					Variables provided by SHA						
	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPENNESS ([w × h]/l)	Earth fill (item 258) (ft)	Number of lanes (item 28a)	Traffic volume (item 29) (vehicles/day)
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	5.18	256.64	1.68	60.00	12.00	230300.00
Mean	9.68	88.84	9.53	8.67	17.42	2.44	1.90	46.36	0.18	9.52	3.29	27757.80
± SE	0.80	1.06	2.33	0.74	0.87	0.06	0.04	2.36	0.01	0.70	0.12	2229.19
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00

Item codes are from “SHA guide for completing structure inventory and appraisal input forms; Office of Bridge Development, June 2003”.

Table 6. Forty species detected by camera traps in culverts over 31,317 trap nights (TN) in 228–265 actively surveilled drainage structure cells during all nine, two-week statewide camera placement cycles from 28 August 2008 to 3 January 2011.

Scientific name	Common name	Culvert cells used	Number captured	Captures / night × 100
Procyon lotor	northern raccoon	246	24,800	79.19
Didelphis virginiana	Virginia opossum	129	1,076	3.44
Felis domesticus	domestic cat	103	2,169	6.93
Marmota monax	woodchuck	97	822	2.62
Ardea herodias	great blue heron	77	545	1.74
Vulpes vulpes	red fox	66	928	2.96
Homo sapiens	human	66	399	1.27
Odocoileus virginianus	white-tailed deer	63	1,903	6.08
Sciurus carolinensis	eastern gray squirrel	53	531	1.70
Rattus norvegicus	Norway rat	52	326	1.04
Urocyon cinereoargenteus	common gray fox	47	294	0.94
Peromyscus spp.	white-footed or deer mouse	33	296	0.95
Anas platyrhynchos	mallard	28	635	2.03
Tamias striatus	eastern chipmunk	28	105	0.34
Castor canadensis	beaver	21	133	0.42
Canis familiaris	domestic dog	19	81	0.26
Mustela vison	American mink	18	39	0.12
Sylvilagus floridanus	eastern cottontail	18	39	0.12
Lutra canadensis	northern river otter	18	51	0.16
Aix sponsa	wood duck	13	50	0.16
Corvus brachyrhynchos	American crow	11	96	0.31
Branta canadensis	Canada goose	10	198	0.63
Mephitis mephitis	striped skunk	8	24	0.08
Ondatra zibethicus	muskrat	7	22	0.07
Turdus migratorius	American robin	6	7	0.02

Table 6. Continued.

Scientific name	Common name	Culvert cells used	Number captured	Captures / night × 100
Hirundo rustica	barn swallow	5	726	2.32
Sayornis phoebe	eastern phoebe	3	34	0.11
Dumetella carolinensis	gray catbird	3	5	0.02
Quiscalus quiscula	common grackle	2	20	0.06
Mustela frenata	long-tailed weasel	2	5	0.02
Butorides virescens	green heron	2	2	0.01
Bos taurus	domestic cattle	1	547	1.75
Melospiza melodia	song sparrow	1	5	0.02
Columba livia	rock pigeon	1	2	0.01
Sturnus vulgaris	European starling	1	1	0.00
Thryothorus ludovicianus	Carolina wren	1	1	0.00
Aythya valisineria	canvasback	1	1	0.00
Nerodia sipedon	northern watersnake	1	1	0.00
Chelydra serpentina	snapping turtle	1	1	0.00
Zapus hudsonius	meadow jumping mouse	1	1	0.00

Table 7. Thirty-two terrestrial vertebrate species sighted live in culverts during camera placement and retrieval. Results are arranged taxonomically and by the order of culvert occurrence frequency.

Scientific name	Common name	Culvert cells used	Number sighted
Odocoileus virginianus	white-tailed deer	9	13
Homo sapiens	human	3	5
Vulpes vulpes	red fox	3	3
Felis domesticus	domestic cat	2	2
Marmota monax	woodchuck	2	2
Sylvilagus floridanus	eastern cottontail	2	2
Sciurus carolinensis	eastern gray squirrel	1	2
Microtus pennsylvanicus [1]	meadow vole	1	1
Peromyscus spp.	white-footed or deer mouse	1	1
Hirundo rustica	barn swallow	11	116
Sayornis phoebe	eastern phoebe	12	23
Anas platyrhynchos	mallard	7	41
Ardea herodias	great blue heron	7	7
Branta canadensis	Canada goose	1	1
Plestiodon fasciatus [1]	common five-lined skink	5	8
Chelydra serpentina	snapping turtle	5	5
Trachemys scripta elegans [1]	red-eared slider	1	1
Chrysemys picta [1]	painted turtle	1	1
Nerodia sipedon	northern watersnake	6	6
Pantherophis alleghaniensis [1]	black ratsnake	3	3
Thamnophis sirtalis [1]	common gartersnake	2	2

Table 7. Continued

Scientific name	Common name	Culvert cells used	Number sighted
Plethodon cinereus [1]	eastern redback salamander	3	3
Desmognathus fuscus [1]	northern dusky salamander	1	100
Eurycea bislineata [1]	northern two-lined salamander	1	1
Lithobates clamitans [1]	green frog	38	138
Lithobates sphenocephalus [1]	southern leopard frog	9	129
Lithobates palustris [1]	pickerel frog	7	10
Lithobates pipiens [1]	northern leopard frog	3	5
Pseudacris crucifer [1]	spring peeper	2	2
Lithobates catesbeianus [1]	bullfrog	2	2
Anaxyrus americanus [1]	American toad	1	1
Lithobates sylvaticus [1]	wood frog	1	1

[1]Seventeen species, primarily herptiles, were never recorded by the infrared, motion-detecting cameras.

Table 8. Comparison of seasonal use of culverts by wildlife species in Maryland. Seasons are bracketed by the spring and fall equinoxes and summer and winter solstices. Means followed by different superscript letters are significantly different based on Tukey B post-hoc test.

Common name	Fall			Winter			Spring			Summer			*F*	df	*P*-value
	n	mean	±SE	*n*	mean	±SE	*n*	mean	±SE	*n*	mean	±SE			
northern raccoon	443	1.14^{a}	1.68	296	0.68^{a}	0.99	442	0.84^{b}	0.04	421	1.57^{c}	0.94	26.578	3, 160	<0.001
Virginia opossum	105	0.27^{a}	0.03	29	0.14^{b}	0.02	76	0.18^{ab}	0.02	108	0.27^{a}	0.3	3.296	3, 313	0.021
domestic cat	98	0.47	0.08	62	0.49	0.10	67	0.49	0.10	86	0.50	0.10	0.015	3, 309	0.998
woodchuck	32	0.15	0.02	5	0.14	0.05	76	0.25	0.08	99	0.33	0.06	0.736	3, 208	0.532
great blue heron	56	0.25	0.40	27	0.21	0.06	36	0.21	0.05	42	0.22	0.05	0.131	3, 157	0.942
red fox	77	0.34	0.04	39	0.24	0.05	46	0.34	0.08	56	0.41	0.06	1.080	3, 214	0.358
humans	23	1.67	0.03	20	0.16	0.02	34	0.25	0.08	24	0.43	0.12	2.368	3, 97	0.075
white-tailed deer	65	0.68^{ab}	0.12	24	0.48^{ab}	0.09	54	0.40^{a}	0.06	57	0.94^{b}	0.17	3.400	3, 196	0.019
eastern gray squirrel	43	0.36	0.08	11	0.27	0.07	31	0.26	0.05	26	0.42	0.12	0.594	3, 107	0.620
Norway rat	27	0.31	0.08	10	0.40	0.14	17	0.23	0.07	29	0.21	0.03	0.863	3, 79	0.464
common gray fox	27	0.25	0.04	18	0.13	0.02	22	0.19	0.04	16	0.42	0.21	1.477	3, 79	0.227
white-footed or deer mouse	14	0.16	0.05	8	0.19	0.04	11	0.56	0.33	15	0.75	0.28	1.568	3, 44	0.211

Table 9. Comparison of regional use of culverts by wildlife in Maryland. Superscript letters that differ among means are significant based on the Least Significant Difference (LSD) post-hoc test.

Common name	Appalachian Mountain *n* = 61		Piedmont *n* = 82		Western Shore *n* = 88		Eastern Shore *n* = 34		*F*	df	*P-value*
	mean	± SE	mean	± SE	mean	± SE	mean	± SE			
northern raccoon	0.68^{a}	0.07	1.14^{b}	0.14	0.55^{a}	0.05	0.44^{a}	0.10	8.760	3, 261	<0.001
Virginia opossum	0.05^{a}	0.01	0.02^{b}	0.00	0.02^{b}	0.00	0.02^{b}	0.01	3.400	3, 261	0.018
domestic cat	0.16^{a}	0.48	0.02^{b}	0.00	0.04^{b}	0.02	0.01^{b}	0.00	4.134	3, 261	0.007
woodchuck	0.02	0.00	0.04	0.01	0.01	0.00	0.01	0.00	2.098	3, 261	0.101
great blue heron	0.01	0.00	0.02	0.01	0.02	0.00	0.03	0.01	0.801	3, 261	0.494
red fox	0.01^{a}	0.00	0.06^{b}	0.01	0.01^{a}	0.00	0.00^{a}	0.00	5.383	3, 261	0.001
humans	0.01	0.00	0.01	0.00	0.01	0.00	0.04	0.04	0.902	3, 261	0.441
white-tailed deer	0.01^{a}	0.06	0.15^{b}	0.04	0.01^{a}	0.00	0.01^{a}	0.02	5.995	3, 261	0.001
eastern gray squirrel	0.02	0.00	0.01	0.00	0.01	0.00	0.00	0.02	1.194	3, 261	0.312
Norway rat	0.00^{a}	0.00	0.01^{b}	0.00	0.00^{a}	0.02	0.01^{ab}	0.01	2.673	3, 261	0.048
common gray fox	0.00	0.00	0.01	0.04	0.00	0.02	0	0	1.027	3, 261	0.381
white-footed or deer mouse	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.04	0.630	3, 261	0.596

Table 10. Summary of Monte Carlo test for 499 permutations under the reduced model for 12 major species and 12 environmental and culvert structural variables.

Test of significance	Measure		
First canonical axis	Eigenvalue	=	0.119
	F-ratio	=	17.793
	P-value	=	0.002
All canonical axes	Trace	=	0.319
	F-ratio	=	4.452
	P-value	=	0.002

Table 11. Summary of the Canonical Correspondence Analysis (CCA) for 12 major species and 12 environmental and culvert structural variables.

	Axes				Total inertia
	1	2	3	4	
Eigenvalues	0.119	0.095	0.047	0.024	1.734
Species-environment correlations	0.630	0.632	0.532	0.404	
Cumulative percentage variance					
of species data	6.9	12.3	15.1	16.4	
of species environment relation	37.4	67.2	82	89.5	
Sum of all eigenvalues					1.734
Sum of all canonical eigenvalues					0.319

Table 12. Summary of Monte Carlo test for 499 permutations under the reduced model for 12 major species and 11 land use/land cover (LULC) variables.

Test of significance	Measure		
First canonical axis	Eigenvalue	=	0.049
	F-ratio	=	7.081
	P-value	=	0.002
All canonical axes	Trace	=	0.165
	F-ratio	=	2.308
	P-value	=	0.002

Table 13. Summary of the Canonical Correspondence Analysis (CCA) for 12 major species and 11 land use/land cover (LULC) variables.

	Axes				Total inertia
	1	2	3	4	
Eigenvalues	0.049	0.036	0.025	0.020	1.734
Species-environment correlations	0.457	0.424	0.385	0.324	
Cumulative percentage variance					
of species data	2.8	4.9	6.3	7.5	
of species environment relation	29.9	51.6	66.2	78.6	
Sum of all eigenvalues					1.734
Sum of all canonical eigenvalues					0.165

Table 14. Comparison of structural variables of culverts with and without a given species. See Figure 5 legend for explanation of variable codes.

	Average water depth (cm)	Visibility of entrance (%)	Distance cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with northern raccoon												
Maximum	76.88	100.00	200.00	90.00	50.00	5.79	5.18	256.64	1.68	60.00	12.00	230300.00
Mean	8.63	88.20	6.53	8.96	17.73	2.44	1.91	45.94	0.18	9.87	3.30	27713.19
± SE	0.72	1.13	1.26	0.79	0.90	0.06	0.04	2.51	0.01	0.76	0.13	2370.99
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	246	246	246	246	246	246	246	246	246	246	246	246
Culverts without northern raccoon												
Maximum	82.50	100.00	500.00	30.00	40.50	5.49	2.11	112.17	0.63	25.00	6.00	106075.00
Mean	25.87	96.45	48.37	5.32	14.24	2.32	1.54	41.36	0.13	5.63	3.21	29133.89
± SE	6.22	1.52	27.43	1.78	3.38	0.26	0.06	6.90	0.03	1.81	0.40	8524.24
Minimum	0.00	80.00	2.00	0.00	0.00	1.22	0.91	7.92	0.03	0.00	1.00	1550.00
n	16	19	17	19	19	19	19	18	18	13	18	11
t-value	–2.753	–4.346	–1.524	1.259	1.032	0.508	4.978	0.496	0.922	1.551	0.187	–0.150
P-value	0.015	<0.001	0.145	0.209	0.303	0.612	<0.001	0.620	0.358	0.122	0.852	0.874

Table 14. Continued.

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with Virginia opossum												
Maximum	30.00	100.00	150.00	57.50	47.00	5.26	5.18	256.64	1.68	60.00	10.00	191575.00
Mean	4.14	86.92	6.23	8.19	17.74	2.31	1.88	47.33	0.16	10.09	3.28	25079.83
± SE	0.38	1.77	1.46	0.90	1.22	0.08	0.06	3.59	0.02	1.04	0.18	2675.43
Minimum	0.00	17.50	0.00	0.00	0.00	1.07	0.61	7.92	0.01	0.00	1.00	325.00
n	129	129	129	129	129	129	129	129	129	129	129	129
Culverts without Virginia opossum												
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	3.56	174.65	1.16	55.00	12.00	230300.00
Mean	15.06	90.57	12.66	9.18	17.23	2.55	1.88	43.98	0.18	9.07	3.30	30441.25
± SE	1.41	1.21	4.34	1.18	1.25	0.09	0.04	3.16	0.02	0.98	0.17	3654.58
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.71	7.32	0.00	0.00	1.00	1075.00
n	133	136	134	136	136	136	136	135	135	130	135	128
t-value	–7.465	–1.703	–1.405	–0.664	0.293	–2.008	–0.050	0.702	–0.742	0.713	–0.102	–1.184
P-value	<0.001	0.090	0.162	0.507	0.770	0.046	0.960	0.483	0.459	0.476	0.919	0.238

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with domestic cat												
Maximum	82.50	100.00	100.00	57.50	47.00	5.26	5.18	197.51	1.04	60.00	10.00	191575.00
Mean	4.67	85.22	5.84	9.40	16.68	2.27	1.92	46.61	0.15	10.08	3.33	28037.14
± SE	0.85	1.90	1.13	1.13	1.29	0.09	0.07	3.76	0.02	1.23	0.20	3714.75
Minimum	0.00	17.50	0.00	0.00	0.00	1.27	0.81	7.92	0.01	0.00	1.00	925.00
n	103	103	103	103	103	103	103	103	103	103	103	103
Culverts without domestic cat												
Maximum	76.88	100.00	500.00	90.00	50.00	5.79	3.56	256.64	1.68	51.00	12.00	230300.00
Mean	12.93	91.07	11.87	8.25	17.99	2.54	1.86	44.98	0.19	9.22	3.27	27669.73
± SE	1.15	1.23	3.75	0.99	1.17	0.08	0.04	3.09	0.02	0.87	0.15	2896.02
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	159	162	160	162	162	162	162	161	161	156	161	154
t-value	–5.772	–2.586	–1.538	0.746	0.751	–2.201	0.735	0.332	–1.371	0.584	0.254	0.078
P-value	<0.001	0.010	0.126	0.457	0.453	0.029	0.463	0.740	0.171	0.560	0.799	0.938

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with woodchuck												
Maximum	32.81	100.00	100.00	50.00	47.50	5.18	4.57	156.97	1.68	45.00	10.00	182050.00
Mean	5.56	84.85	5.69	6.73	14.12	2.34	1.87	36.50	0.20	7.29	3.01	20863.23
± SE	0.71	1.95	1.15	0.99	1.40	0.09	0.06	2.61	0.03	0.90	0.19	2864.45
Minimum	0.00	25.00	0.00	0.00	0.00	0.71	0.61	7.92	0.00	0.00	1.00	1275.00
n	97	97	97	97	97	97	97	97	97	97	97	97
Culverts with out woodchuck												
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	5.18	256.64	1.16	60.00	12.00	230300.00
Mean	12.11	91.07	11.74	9.83	19.42	2.49	1.89	50.87	0.16	10.83	3.46	31887.99
± SE	1.18	1.22	3.62	1.02	1.09	0.08	0.04	3.38	0.02	0.98	0.16	3166.31
Minimum	0.00	15.00	0.00	0.00	0.00	1.22	0.76	7.32	0.01	0.00	1.00	325.00
n	165	168	166	168	168	168	168	167	167	162	167	160
t-value	–4.739	–2.708	–1.590	–2.173	–2.967	–1.159	–0.335	–3.362	1.356	–2.661	–1.785	–2.582
P-value	<0.001	0.007	0.114	0.031	0.003	0.247	0.738	0.001	0.176	0.008	0.075	0.010

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with great blue heron												
Maximum	46.25	100.00	200.00	50.00	47.00	4.88	4.57	112.17	1.68	55.00	6.00	176100.00
Mean	12.77	93.18	6.43	5.36	14.42	2.91	2.08	32.84	0.31	6.91	2.78	21002.39
± SE	1.33	1.35	2.57	0.98	1.54	0.13	0.07	2.77	0.04	1.29	0.15	3646.53
Minimum	0.19	50.00	0.00	0.00	0.00	1.37	0.81	7.32	0.03	0.00	1.00	1400.00
n	77	77	77	77	77	77	77	77	77	77	77	77
Culverts without great blue heron												
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	5.18	256.64	1.16	60.00	12.00	230300.00
Mean	8.40	87.00	10.85	10.06	18.74	2.24	1.80	50.85	0.12	10.62	3.50	30672.27
± SE	1.00	1.38	3.16	0.96	1.05	0.06	0.04	3.08	0.01	0.85	0.16	2831.66
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.92	0.00	0.00	1.00	325.00
n	185	188	186	188	188	188	188	187	187	182	187	180
t-value	2.476	3.205	–0.853	–3.432	–2.263	4.852	3.335	–4.343	4.932	–2.413	–3.331	–1.946
P-value	0.014	0.002	0.394	0.001	0.024	<0.001	0.001	<0.001	<0.001	0.017	0.001	0.053

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with red fox												
Maximum	17.00	100.00	12.00	50.00	50.00	4.88	4.57	197.51	0.95	60.00	10.00	191575.00
Mean	3.94	87.16	3.57	12.52	23.53	2.24	1.92	62.53	0.10	14.61	4.00	45695.56
± SE	0.40	2.40	0.36	1.35	1.48	0.10	0.06	4.41	0.02	1.60	0.28	5578.26
Minimum	0.00	17.50	0.00	0.00	0.00	1.07	1.07	7.92	0.01	0.00	1.00	1450.00
n	66	66	66	66	66	66	66	66	66	66	66	66
Culverts without red fox												
Maximum	82.50	100.00	500.00	90.00	47.50	5.79	5.18	256.64	1.68	55.00	12.00	230300.00
Mean	11.62	89.34	11.52	7.43	15.47	2.50	1.87	40.00	0.20	7.90	3.06	21882.62
± SE	1.04	1.17	3.12	0.87	1.02	0.07	0.04	2.71	0.02	0.76	0.13	2260.30
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	196	199	197	199	199	199	199	198	198	193	198	191
t-value	–6.863	–0.884	–2.534	–2.993	4.485	–2.146	0.675	4.217	–3.590	3.795	3.083	3.956
P-value	<0.001	0.378	0.012	0.003	<0.001	0.034	0.501	<0.001	<0.001	<0.001	0.003	<0.001

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with humans												
Maximum	35.00	100.00	50.00	50.00	40.50	5.79	5.18	137.16	1.16	60.00	12.00	230300.00
Mean	6.21	92.42	4.86	12.14	17.77	2.71	2.06	48.02	0.19	11.66	3.46	36205.05
± SE	0.94	1.68	0.80	1.69	1.72	0.14	0.09	4.05	0.03	1.77	0.27	5794.49
Minimum	0.00	37.50	0.00	0.00	0.00	1.37	1.22	9.14	0.02	0.00	1.00	1275.00
n	66	66	66	66	66	66	66	66	66	66	66	66
Culverts without humans												
Maximum	82.50	100.00	500.00	90.00	50.00	5.49	4.57	256.64	1.68	50.00	10.00	191575.00
Mean	10.83	87.59	11.07	7.55	17.39	2.34	1.82	44.81	0.17	8.86	3.24	25144.35
± SE	1.02	1.30	3.10	0.81	1.02	0.06	0.04	2.88	0.02	0.74	0.13	2352.13
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	196	199	197	199	199	199	199	198	198	193	198	191
t-value	–3.316	2.279	–1.940	2.450	0.187	2.366	2.494	0.581	0.607	1.462	0.742	1.769
P-value	0.001	0.024	0.054	0.016	0.852	0.020	0.015	0.562	0.544	0.147	0.422	0.038

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with white-tailed deer												
Maximum	46.25	100.00	200.00	90.00	47.50	5.18	4.57	256.64	1.68	35.00	12.00	230300.00
Mean	6.16	88.77	7.03	11.98	20.63	2.99	2.24	61.52	0.21	10.52	4.10	41351.38
± SE	0.90	2.28	3.24	1.85	1.54	0.13	0.08	5.57	0.04	1.17	0.31	5798.14
Minimum	0.00	17.50	0.00	0.00	0.00	1.42	0.99	9.14	0.01	0.00	1.00	575.00
n	63	63	63	63	63	63	63	63	63	63	63	63
Culverts without white-tailed deer												
Maximum	82.50	100.00	500.00	65.00	50.00	5.79	5.18	197.51	1.16	60.00	10.00	191575.00
Mean	10.80	88.80	10.32	7.67	16.50	2.26	1.77	40.65	0.16	9.25	3.04	23599.12
± SE	1.02	1.21	2.91	0.78	1.03	0.06	0.04	2.51	0.01	0.87	0.12	2312.18
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	199	202	200	202	202	202	202	201	201	196	201	194
t-value	–3.404	–0.013	–0.588	2.475	2.234	5.510	5.213	3.822	1.159	0.764	3.161	2.844
P-value	0.001	0.990	0.557	0.014	0.027	<0.001	<0.001	<0.001	0.250	0.446	0.002	0.006

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with eastern gray squirrel												
Maximum	33.75	100.00	50.00	40.00	47.00	5.26	5.18	256.64	1.68	50.00	10.00	176100.00
Mean	5.85	87.97	4.58	7.77	17.85	2.42	2.08	42.32	0.24	8.12	3.28	27054.53
± SE	1.05	2.35	1.09	1.18	1.96	0.13	0.11	5.83	0.04	1.34	0.28	5263.72
Minimum	0.00	37.50	0.00	0.00	0.00	1.07	1.07	7.92	0.01	0.00	2.00	575.00
n	53	53	53	53	53	53	53	53	53	53	53	53
Culverts without eastern gray squirrel												
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	4.57	197.51	1.16	60.00	12.00	230300.00
Mean	10.65	89.00	10.78	8.93	17.39	2.44	1.83	47.56	0.16	9.91	3.29	28009.67
± SE	0.97	1.20	2.92	0.89	0.98	0.07	0.04	2.61	0.01	0.83	0.13	2532.68
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	209	212	210	212	212	212	212	211	211	206	211	204
t-value	–3.357	–0.386	–1.049	–0.617	0.210	–0.154	2.102	–0.691	1.805	–1.141	–0.036	–0.169
P- value	0.001	0.700	0.295	0.538	0.834	0.877	0.040	0.490	0.076	0.319	0.971	0.866

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with Norway rat												
Maximum	51.56	100.00	200.00	50.00	39.00	5.18	3.05	132.89	1.02	30.00	12.00	230300.00
Mean	7.04	86.60	7.84	5.78	14.13	2.52	1.85	40.82	0.17	6.75	3.35	25081.96
± SE	1.39	2.84	3.87	1.25	1.70	0.13	0.06	3.83	0.03	1.09	0.29	4986.55
Minimum	0.00	17.50	1.00	0.00	0.00	1.30	1.22	9.14	0.03	0.00	1.00	1275.00
n	52	52	52	52	52	52	52	52	52	52	52	52
Culverts without Norway rat												
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	5.18	256.64	1.68	60.00	10.00	191575.00
Mean	10.34	89.33	9.97	9.41	18.30	2.41	1.89	47.91	0.18	10.20	3.28	28488.75
± SE	0.95	1.13	2.77	0.87	1.00	0.07	0.04	2.83	0.02	0.84	0.13	2566.44
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	210	213	211	213	213	213	213	212	212	207	212	205
t-value	–1.963	–1.020	–0.356	–2.378	–2.118	0.703	–0.358	–0.994	–0.021	–2.509	0.223	–0.595
P-value	0.052	0.309	0.722	0.019	0.037	0.483	0.720	0.321	0.983	0.014	0.823	0.552

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with common gray fox												
Maximum	19.25	100.00	12.00	90.00	50.00	4.88	3.56	197.51	1.68	60.00	10.00	191575.00
Mean	4.64	88.14	3.64	13.75	22.05	2.25	1.91	58.20	0.13	12.85	3.68	38288.37
± SE	0.56	2.55	0.45	2.25	2.05	0.13	0.08	5.47	0.04	1.93	0.31	6246.42
Minimum	0.00	25.00	0.00	0.00	0.00	1.27	1.27	9.14	0.02	0.00	1.00	2099.00
n	47	47	47	47	47	47	47	47	47	47	47	47
Culverts without common gray fox												
Maximum	82.50	100.00	500.00	65.00	45.00	5.79	5.18	256.64	1.16	55.00	12.00	230300.00
Mean	10.79	88.94	10.84	7.61	16.50	2.47	1.88	43.91	0.18	8.83	3.21	25528.90
± SE	0.97	1.17	2.86	0.75	0.95	0.07	0.04	2.64	0.01	0.75	0.13	2399.50
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	215	218	216	218	218	218	218	217	217	212	217	210
t-value	–5.495	–0.286	–1.172	2.593	2.452	–1.430	0.366	2.477	–1.294	2.184	1.505	2.161
P-value	<0.001	0.775	0.242	0.012	0.015	0.154	0.715	0.014	0.197	0.030	0.134	0.032

Table 14. Continued

	Average water depth (cm)	Visibility of entrance (%)	Distance to cover (m)	Distance to road (m)	Slope (º)	WIDTH (m)	HEIGHT (m)	LENGTH (m)	OPEN-NESS ([w × h]/l)	Earth fill (ft)	Number of lanes	Traffic volume (vehicles/day)
Culverts with white-footed or deer mouse												
Maximum	27.00	100.00	10.00	27.50	44.00	4.78	4.57	170.69	0.94	35.00	7.00	67575.00
Mean	4.78	87.27	3.24	6.43	16.92	2.12	1.91	45.78	0.15	8.39	3.09	20696.39
± SE	0.87	4.02	0.45	1.22	2.16	0.14	0.12	6.04	0.04	1.56	0.27	3238.06
Minimum	0.06	17.50	1.00	0.00	0.00	1.07	1.07	10.36	0.01	0.00	2.00	925.00
n	33	33	33	33	33	33	33	33	33	33	33	33
Culverts without white-footed or deer mouse												
Maximum	82.50	100.00	500.00	90.00	50.00	5.79	5.18	256.64	1.68	60.00	12.00	230300.00
Mean	10.39	89.01	10.46	9.02	17.56	2.48	1.88	46.59	0.18	9.72	3.32	28861.08
± SE	0.91	1.08	2.69	0.83	0.95	0.06	0.04	2.60	0.02	0.78	0.13	2566.56
Minimum	0.00	15.00	0.00	0.00	0.00	0.71	0.61	7.32	0.00	0.00	1.00	325.00
n	229	232	230	232	232	232	232	231	231	226	231	224
t-value	–4.459	–0.538	–1.015	–1.751	–0.270	–2.384	0.286	0.027	0.548	–0.604	–0.628	–1.976
P-value	<0.001	0.591	0.311	0.084	0.788	0.044	0.775	0.978	0.584	0.546	0.530	0.052

Figure 1. Culvert 15138X0 is 11 feet, 10 inches (3.6 m) wide, 7 feet 7 inches (2.3 m) tall, and 256 feet (78.8 m) long with 6 inches (15 cm) of water. This arch culvert cell had a gravel and sand substrate.

Figure 2. Culvert 02015X0 is 8 feet (2.4 m) wide, 6 feet (1.8 m) tall by 104 feet (31.7 m) long with 3 inches (7.6 cm) of water. This box culvert cell had a concrete substrate.

Figure 3. Culvert 02159X0 functions as an equestrian underpass. It is 15 feet (4.5 m) in diameter, 242 feet (73.7 m) long, and essentially dry. This cylinder culvert cell has 5 feet, 10 inches (1.8 m) of type 1 fencing and a gravel substrate.

Figure 4. Installation of an infrared, motion-detecting trail camera on an angle bracket in a box culvert.

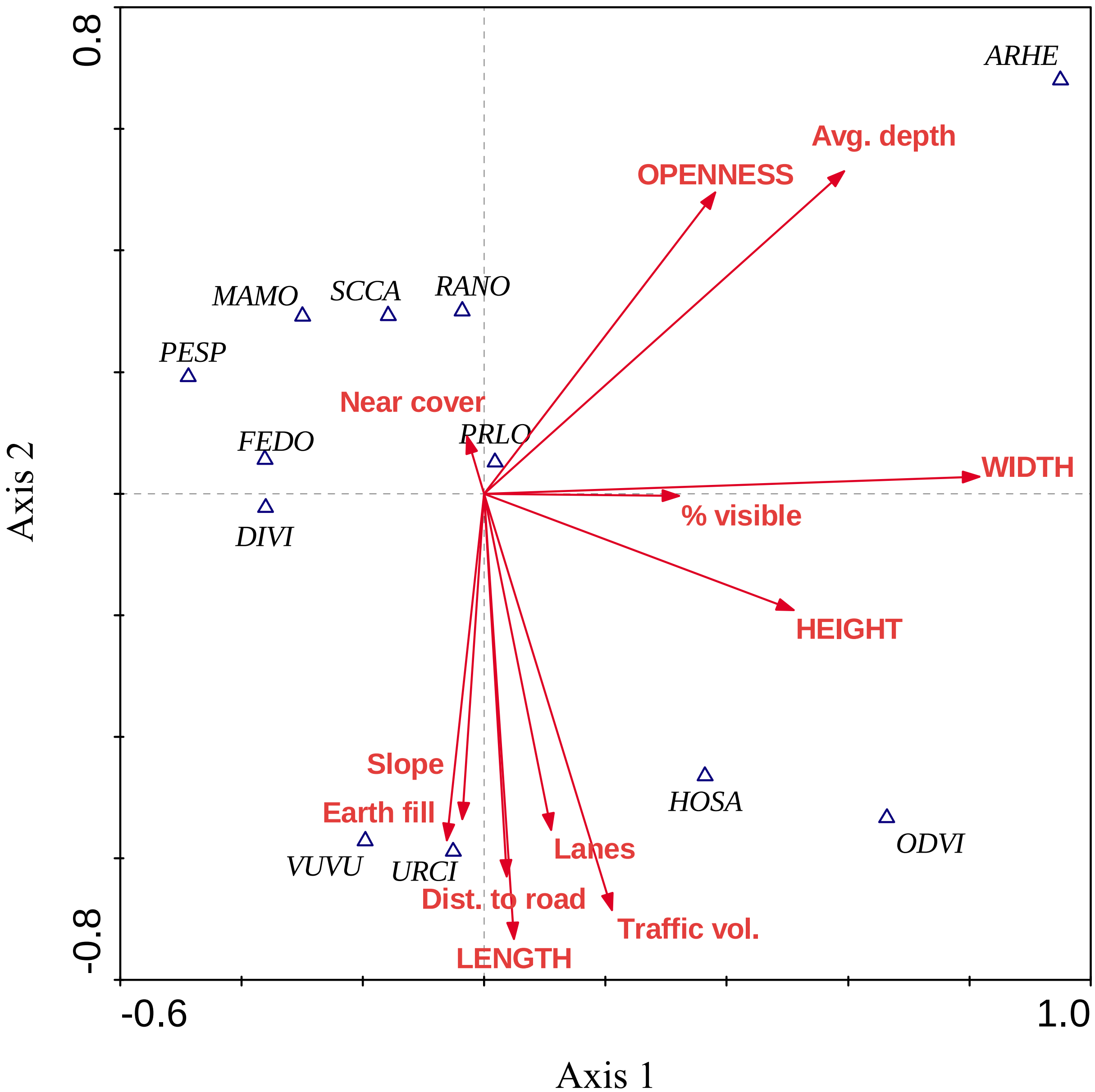

Figure 5. Canonical Correspondence Analysis (CCA) biplot of 12 vertebrate species (Δ) and 12 environmental and structural variables (arrows) related to the use of road drainage structures by wildlife in Maryland. The species are: PRLO = *Procyon lotor* (northern raccoon), DIVI = *Didelphis virginianus* (Virginia opossum), FEDO = *Felis domesticus* (domestic cat), MAMO = *Marmota monax* (woodchuck), ARHE = *Ardea herodias* (great blue heron), VUVU = *Vulpes vulpes* (red fox), HOSA = *Homo sapiens* (human), ODVI = *Odocoileus virginianus* (white-tailed deer), SCCA = *Sciurus carolinensis* (eastern gray squirrel), RANO = *Rattus norvegicus* (Norway rat), URCI = *Urocyon cinereoargenteus* (common gray fox), and PESP = *Peromyscus* spp. (white-footed or deer mouse). The environmental and structural variables are: Avg. depth = average depth of water, WIDTH = width of culvert, HEIGHT = height of culvert, LENGTH = length of culvert, OPENNESS = culvert openness (width × height/length), Traffic vol. = mean annual average daily traffic volume, Lanes = number of traffic lanes, Dist. to road = distance from the culvert opening to the road edge, Earth fill = the minimum height of earth fill measured

from the top of the culvert to the bottom of the paved surface, Slope = degrees of slope from the top of the culvert to the edge of the paved surface, % visible = mean percent visibility of the culvert opening, and Near cover = proximity of nearest woody vegetation. Environmental variables in all capital letters are culvert structural dimensions. The arrows representing the environmental variables indicate the direction of maximum change of that variable across the diagram. For example, the arrow for WIDTH points to the right of the diagram, indicating that width is increasing along a gradient from left to right. The length of the arrow is proportional to the rate of change, so a long WIDTH arrow indicates a large change and the proximity to the axis indicates that change in WIDTH is strongly correlated with the ordination axis and thus with the community variation shown by the diagram.

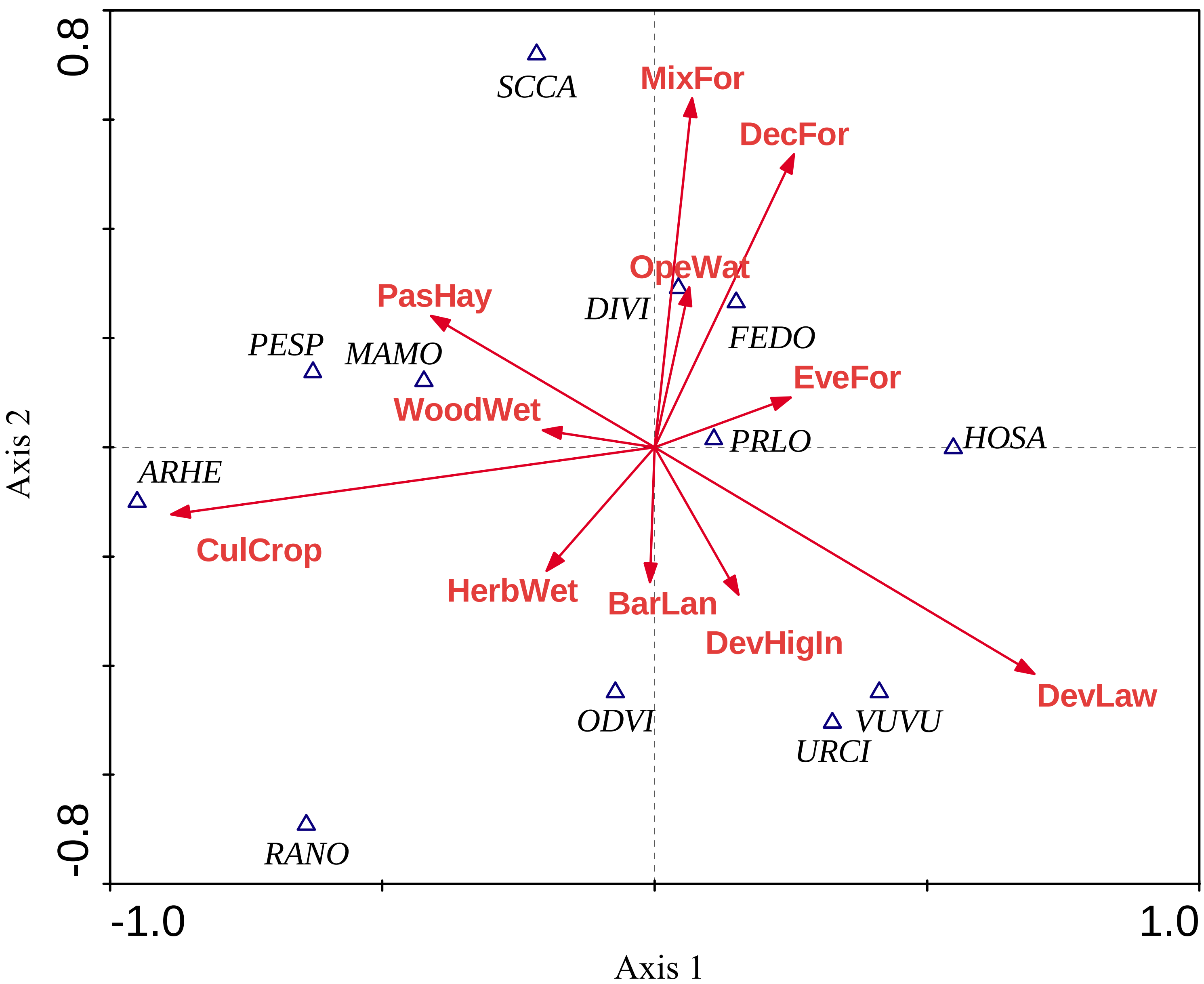
0.8
-0.8
Axis 2
-1.0
1.0
Axis 1
SCCA
MixFor
DecFor
OpeWat
PasHay
DIVI
FEDO
PESP
MAMO
EveFor
WoodWet
PRLO
HOSA
ARHE
CulCrop
HerbWet
BarLan
DevHigIn
DevLaw
ODVI
VUVU
URCI
RANO

Figure 6. Canonical Correspondence Analysis (CCA) biplot shows the 12 most frequently occurring vertebrate species (Δ) in road drainage structures in Maryland and their association with 13 Land Use/Land Cover (LULC) variables (arrows) found within 1 km of each culvert. The LULC variables are: OpeWat = Open water, DevLaw = Developed open space/lawns, DevHighIn = Developed high intensity or urban, BarLan = Barren land without vegetation cover, DecFor = Deciduous forest, EveFor = Evergreen forest, MixFor = Mixed evergreen and deciduous forest, PasHay = Pasture/hay, CulCrop = Cultivated crops, WoodWet = Woody wetlands, and HerbWet = Herbaceous wetlands. The length and direction of the arrows indicate the relative degree and direction of association. See Figure 5 for species codes.

Figure 7. A great blue heron is photographed with fish prey. Great blue herons used culverts having deeper water and more open dimensions.

Figure 8. A northern raccoon is shown using a cylinder culvert that is half filled with sediment and flooded. Northern raccoons were found to use culverts of all shapes and sizes surrounded by a variety of habitat types.

Figure 9. A woodchuck is caught using an existing ledge in a box culvert.

Figure 10. Humans used culverts for transit under highways. A bicyclist is shown traveling through a large cylinder culvert.

Figure 11. An adult doe found with her young in a box culvert. Deer often travel in family groups through culverts, perhaps familiarizing their offspring with these travel routes.

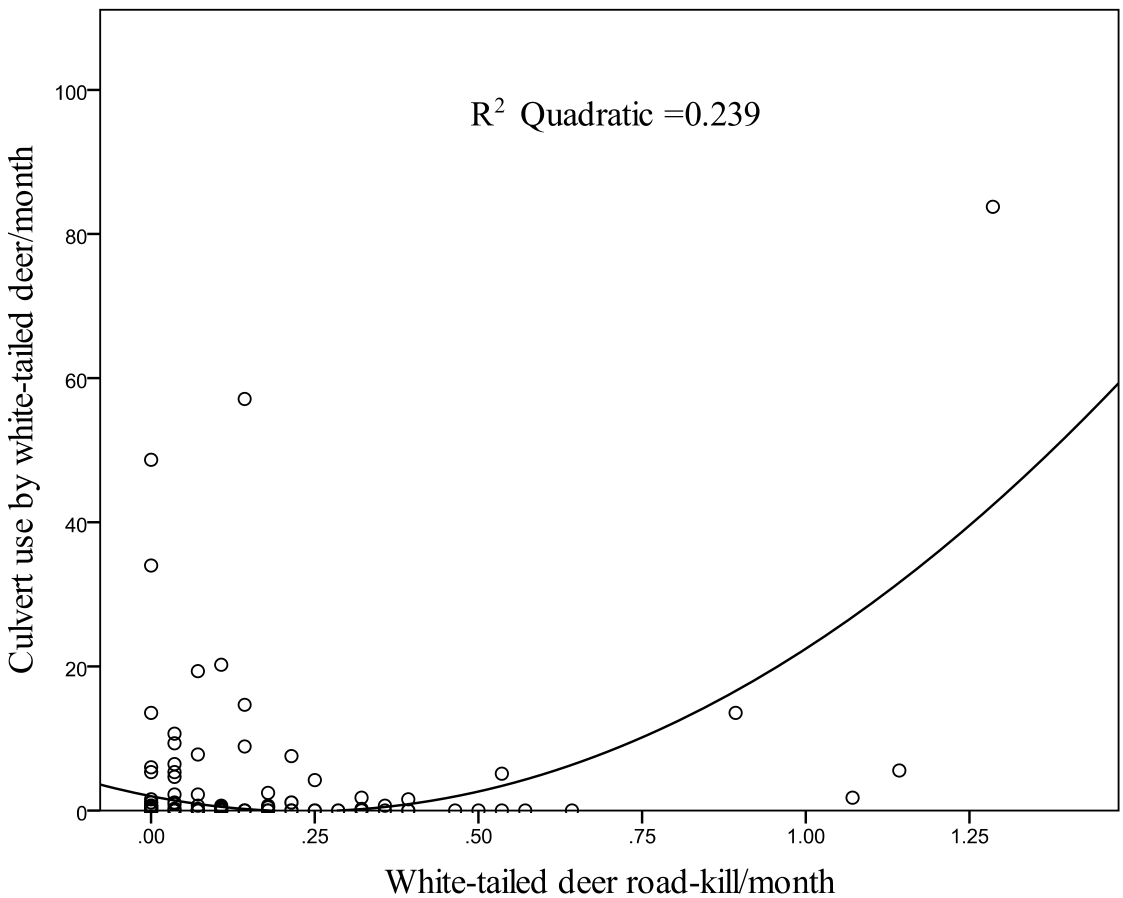

Figure 12. The relationship between the use of culvert sites by white-tailed deer documented by camera traps and occurrence of road-killed, white-tailed deer as documented by the Maryland State Highway Administration Large Animal Removal Reporting System (LARRS) during the time period 28 August 2008–3 January 2011. The slope (culvert use by white-tailed deer: $\hat{Y} = 1.984 - 17.870x + 38.337x^2$ [where x = deer road-kill rate]) was significant ($F_{[2, 233]} = 36.603$, $P \leq 0.001$); but, the association was not very strong ($R^2 = 0.239$).

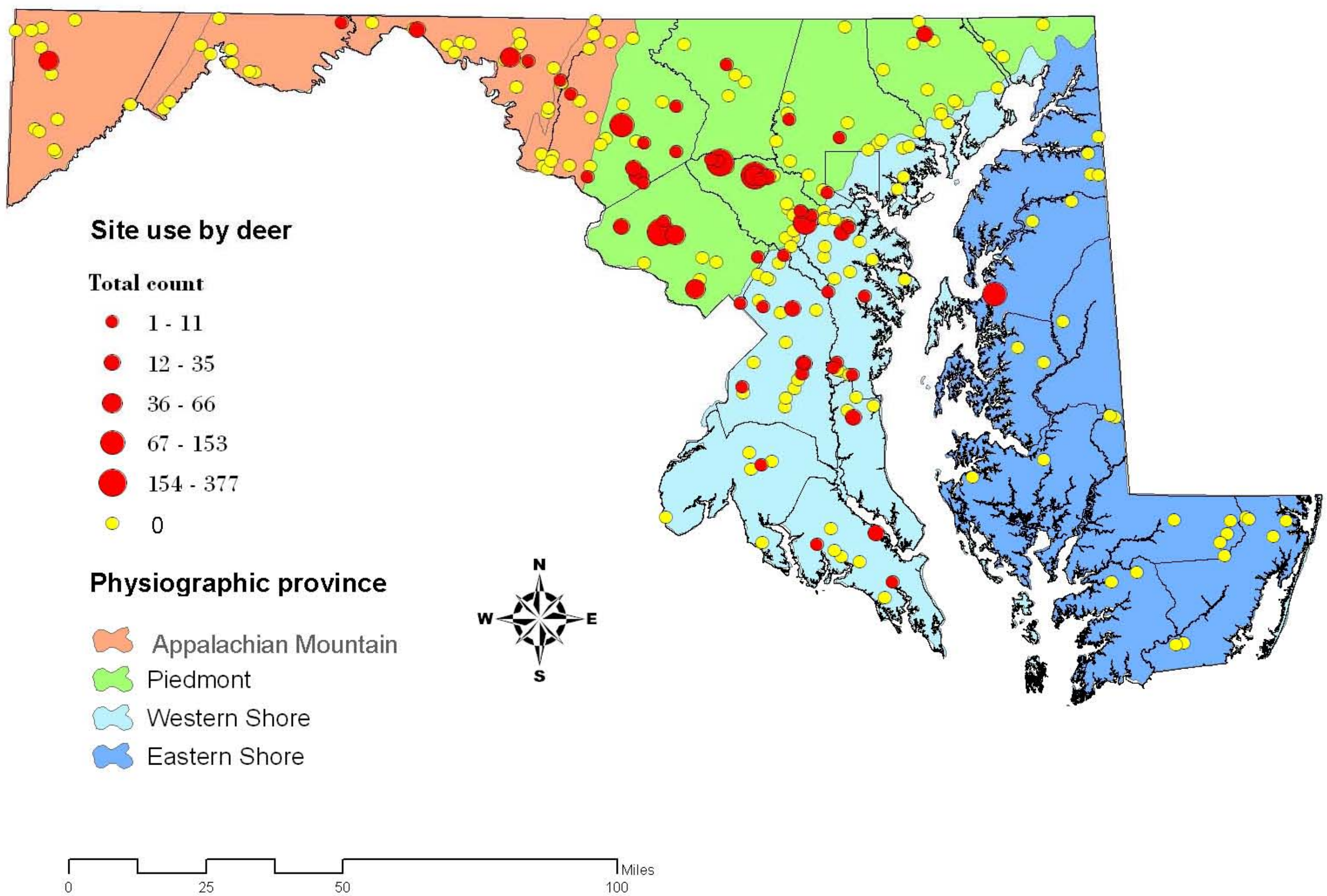

Figure 13. Culvert sites used by white-tailed deer (*n* = 59) compared to sites not used by white-tailed deer (*n* = 177) during this study. The highest use of culvert sites by white-tailed deer occurred in central Maryland, i.e., the Piedmont physiographic province.

Figure 14. Barn swallow nestlings in a nest on the wall of a box culvert in Maryland.

Figure 15. Eastern phoebe nestlings in a nest on a wall of a box culvert in Maryland.

Figure 16. Canada goose and goslings use a box culvert. Culverts are an integral part of the waterways used by waterfowl in Maryland.