

Wildlife-vehicle collision hotspots at US highway extents: scale and data source effects

Fraser M. Shilling¹, David P. Waetjen²

1 *Fraser M. Shilling*¹, *Department of Environmental Science and Policy, University of California, One Shields Avenue, Davis CA 95616* **2** *Department of Environmental Science and Policy, University of California, One Shields Avenue, Davis CA 95616*

Corresponding author: *Fraser M. Shilling* (fmshilling@ucdavis.edu)

Academic editor: *A. Seiler* | Received 31 December 2014 | Accepted 18 June 2015 | Published 28 July 2015

<http://zoobank.org/802A87D6-374A-420B-90BE-58EF8FBA61C3>

Citation: Shilling FM, Waetjen DP (2015) Wildlife-vehicle collision hotspots at US highway extents: scale and data source effects. In: Andreas Seiler A, Hedin J-O (Eds) Proceedings of IENE 2014 International Conference on Ecology and Transportation, Malmö, Sweden. Nature Conservation 11: 41–60. doi: 10.3897/natureconservation.11.4438

Abstract

Highways provide commuter traffic and goods movement among regions and cities through wild, protected areas. Wildlife-vehicle collisions (WVC) can occur frequently when wildlife are present, impacting drivers and animals. Because collisions are often avoidable with constructed mitigation and reduced speeds, transportation agencies often want to know where they can act most effectively and what kinds of mitigation are cost-effective. For this study, WVC occurrences were obtained from two sources: 1) highway agencies that monitor carcass retrieval and disposal by agency maintenance staff and 2) opportunistic observations of carcasses by participants in two statewide systems, the California Roadkill Observation System (CROS; <http://wildlifecrossing.net/california>) and the Maine Audubon Wildlife Road Watch (MAWRW; <http://wildlifecrossing.net/maine>). Between September, 2009 and December 31, 2014, >33,700 independent observations of >450 vertebrate species had been recorded in these online, form-based informatics systems by >1,300 observers. We asked whether or not WVC observations collected by these extensive, volunteer-science networks could be used to inform transportation-mitigation planning. Cluster analyses of volunteer-observed WVC were performed using spatial autocorrelation tests for parts or all of 34 state highways and interstates. Statistically-significant WVC hotspots were modeled using the Getis-Ord G_i^* statistic. High density locations of WVC, that were not necessarily hotspots, were also visualized. Statistically-significant hotspots were identified along ~7,900 km of highways. These hotspots are shown to vary in position from year to year. For highways with frequent deer-vehicle collisions, annual costs from

collisions ranged from US\$0 to >US\$30,000/km. Carcass clusters from volunteer data had very little or no overlap with similar findings from agency-collected WVC data, during a different time-range. We show that both state agency-collected and volunteer-collection of WVC observations could be useful in prioritizing mitigation action at US state-scales by state transportation agencies to protect biodiversity and driver safety. Because of the spatial extent and taxonomic accuracy at which volunteer observations can be collected, these may be the most important source of data for transportation agencies to protect drivers and wildlife.

Keywords

Transportation, Wildlife-Vehicle Collisions, Roadkill, Informatics, Citizen Science, Wildlife Observation, Wildlife Movement

Introduction

Wildlife-vehicle collisions (WVC) are a large and growing concern among Departments of Transportation (DOT), conservation organizations and agencies, and the driving public (Huijser et al. 2008). WVC is a safety concern for drivers (Bissonette et al. 2008) and a conservation concern for most animal species (Fahrig and Rytwinski 2009). Recently, Loss et al. (2014) estimated that between 89 and 340 million birds may die per year in the US from collisions with vehicles. Many DOTs are trying different methods of reducing WVC, including fencing roadways and providing crossing structures across the right-of-way to allow safe animal passage. WVC occur when traffic coincides with a place where animals decide to cross the surface of a roadway. Predicting and prioritizing these places for mitigation of impacts to wildlife and drivers is an important step in reducing the conflict. To inform these types of predictions and corresponding mitigation at a large scale (e.g., a US state), it becomes necessary to collect accurate, extensive, long-term WVC data.

Monitoring biodiversity and investigating causes of changes in biodiversity allows society to make decisions about conservation (Wilson 1999; Devictor et al. 2010; Bang and Faeth 2011; Corona et al. 2011) and improve management of human-wildlife conflict. Volunteer-science provides a large and robust pool of enthusiastic people interested in problem-solving and data collection. Furthermore, volunteer-science has facilitated analysis of ecological processes operating at broad spatial and temporal scales, far beyond the limit of traditional field studies (Wilson et al. 2013). Some of the largest wildlife-observation systems in the world rely primarily on volunteer effort to develop reliable, verified wildlife data (Schmeller et al. 2009; Ryder et al. 2010; Cooper et al. 2014). These volunteers are often professional biologists making wildlife observations in their free time and contributing these observations to various wildlife reporting systems (e.g. California Roadkill Observation System, CROS). One perception of volunteer science collected data is that they may suffer from observer bias and identification error (Cooper et al. 2014). However, this has not often been the case, and inaccuracies may be outweighed by the size of datasets available from volunteers (Schmeller et al. 2009; Ryder et al. 2010). As the volunteer science movement becomes

an industry, it is anticipated that data collection will become more streamlined and standardized, with the volunteer scientist benefiting from the knowledge that they have helped advance in a scientific field they are passionate about. Informatics is a discipline that provides tools useful to collect, manage, and use diverse types of data to support research and management. Conservation-oriented analysis of ecological data collected by volunteers in standardized web-based informatics systems is a critical component of feedback to volunteers and can be an effective use of the data.

Volunteer and Agency Reporting of Road-Associated Wildlife

Globally, there are dozens of web-based systems for reporting WVC. For example, the Swedish National Wildlife Accident Council maintains a website for official reporting of accidents involving animals (<http://www.viltolycka.se/hem/>). The system is operated by the Swedish National Police, and it is the largest agency-owned WVC-reporting system in the world with over 200,000 records of WVC in the last five years. Online reporting and data display has been in place since 2010, but data from police records of accidents are available back to 1985. The largest, longest-running system that relies on volunteer-observers reporting any vertebrate species is the California Roadkill Observation System (CROS), maintained by the Road Ecology Center at the University of California-Davis (<http://www.wildlifecrossing.net/california>). In the US, the Idaho Department of Fish and Game operates the Idaho Fish and Wildlife Information System – IFWIS (<https://fishandgame.idaho.gov/species/roadkill>). The system allows entry of observation of any carcass resulting from WVC and as of 12/2014 had >22,000 records. Many observation systems have appeared over the last five years and they vary in their specific purpose, taxonomic breadth, and use of social networks for collecting data and outreach. A few use smartphone-based applications to facilitate data entry from the field (Olson et al. 2014) and some use social media and communication tools to receive observations (e.g., Project Splatter in the UK, <http://projectsplatter.co.uk/>). One purpose of this study was to find out whether it is possible to use the data from web-based informatics systems containing volunteer wildlife observations, to plan for WVC mitigation at the scale of US states.

Existing WVC reporting systems can consist of tens of thousands of data points and represent a potential source of “big data” for road ecology, community ecology, transportation mitigation, biodiversity mapping, and other scientific/engineering disciplines. Big data refers to datasets that are large and usually geographically extensive, and so require novel solutions for storage, analysis, processing and visualization (Hampton et al. 2013). At the US state scale and possibly at a global level, WVC reporting systems provide the largest known, continuous source of data on the occurrence and distribution of a wide taxonomic range of wildlife whilst also providing opportunities for tissue sampling of genetics, disease, and other testing. Carefully structured informatics (i.e. collection, storage, management, and sharing) systems for these observations facilitate ecological analyses and other biological uses of the data.

Spatial clustering of WVC

One common finding with spatial analysis of WVC is that collisions are clustered, which often leads to analysis of proximate causes of clustering for individual species (e.g., road or landscape features; Gunson et al. 2011). One approach is to use previous collisions to develop predictive landscape models to find “hotspots” (Nielsen et al. 2003; Langen et al. 2009; Gunson et al. 2011; Bil et al. 2013), or seasonality models to find “hot moments” (Beaudry et al. 2010). This is often done for ungulates because collisions with ungulates are both a conservation and safety concern (e.g., Danks and Porter 2010). There are various costs associated with a collision between a deer and a vehicle; on average, a collision with a deer costs \$6,671 to society (Hujser et al. 2009). This approach means that WVC can be measured in terms of their cost to society, which can matter regardless of clustering of WVC. Less well-studied than WVC clustering is the idea that for broad taxonomic groups, “sheet flow” of animals may result in WVC everywhere and statistically-significant clustering may only be found because of limitations in the study area, or data collection. For highway planning, it is important to understand the clustering for individual species in each of their habitats and landscapes, and determine the reasons why higher WVC occurs on that stretch of road.

There are many tools to measure impacts to species from WVC, to determine causes and correlations with WVC, and for finding places where transportation agencies can focus remedial action to reduce impacts to wildlife and improve driver safety. Analysis to identify non-random clusters of single or multiple species WVC’s (hotspots) has utilized GIS (Geographic Information Systems); a promising tool where statistics have been used to identify spatial clusters. Examples of analytical approaches and methods include: Nearest Neighbor Index (e.g. Matos et al. 2012); ‘Satscan’, borrowed from epidemiological studies, which looks for non-random clusters of events (i.e. disease outbreaks, Ball et al. 2008); the Getis-Ord- G_i^* statistic for spatial autocorrelation (Getis and Ord 1992); and the Kernel Density Estimator Plus method for estimating locations of high densities of events (Bil, personal communication).

We hypothesize that volunteer-collected observations of WVC could be used to prioritize roadway sections for mitigation action. We describe the use of data from state-scale, online observational networks for roadkill/wildlife occurrences in California (CA) and Maine (ME). We found that there were sufficient data to identify statistically-significant “hotspots” for many of the states’ highways. We propose that novel online, volunteer-based systems could be used to augment the efforts of state DOTs and wildlife agencies and help inform location and type of mitigation actions.

Methods

We used a spatial-autocorrelation test (Getis Ord, G_i^*) to determine the significance of WVC differences among neighboring roadway segments, where significance was set at $p < 0.05$. The two states were chosen for the availability of existing large-scale, online

systems of volunteer-collected WVC data. At the time of writing, both systems were being actively used. The California Roadkill Observation System (CROS, <http://www.wildlifecrossing.net/california>) was launched in August 2009 to allow volunteer scientists to record carcass observations on California roads and highways. California has a population of more than 37 million people and >499,000 km of roadways networked across 411,000 km² of varied land cover types, including urban, agriculture, forests, grasslands, and desert. Of these roadways, 196,381 km are major roads, and 25,041 km are highways. Eighteen example highways were chosen in CA for geospatial analysis: interstates 5, 80, 280, and 580 and state routes (SR) 1, 3, 4, 13, 17, 20, 37, 49, 50, 70, 94, 99, 101, and 190. A similar system was developed in early 2010 for Maine, the Maine Audubon Wildlife Road Watch (<http://www.wildlifecrossing.net/maine>), to allow collection of both live and dead animal observations on and immediately adjacent to Maine's roads and highways. Maine has a population of 1,328,000 people and >60,600 km of roads, including 10,900 km of highways, across its 84,000 km² of forests, wetlands, agricultural areas and townships. Parts or all of 16 example highways were chosen in ME for geospatial analysis: interstate 29 and state routes 1, 2, 4, 7, 9, 16, 17, 100A, 111, 116, 126, 127, 128, 139, and 202.

WVC data collection

Volunteer-collected data were downloaded for each of CA and ME from their respective online systems. Date ranges for CA August, 2009 to October, 2014 and for ME were June, 2010 to November, 2014. WVC (n = 12,064) for specific highways were selected by hand in GIS based on their proximity to the highway. Any question about which of adjacent roadways a WVC was associated with was resolved by referring to the WVC record, which includes a narrative description of the site of observation.

The California Department of Transportation (Caltrans) maintains databases for carcass retrieval by District maintenance staff and for deer-vehicle-collisions (DVC) requiring a report and attendance by the California Highway Patrol. Partially-complete data-sets were retrieved from Caltrans using a request under the California Public Records Act. Data for portions of two Districts (3 & 4), were the most complete for carcass retrieval and accident reporting. Carcass retrieval data for 1984-1997 and 2001-2009 and DVC data for 2008-2010 were obtained for District 3, I-80 and SR50, and carcass/DVC data for 2005-2012 were obtained for District 4, I-280. DVC were summarized by tenth post-mile for each highway. Data from transportation-maintenance staff in Maine were not available at the time of the study.

Transportation management nexus: WVC hotspot analysis

Two types of "hotspot" analysis were conducted: a test for spatial autocorrelation, which identifies highway segments statistically-different from their neighbors, and

calculation of WVC-density (# WVC/km-year), which allows comparison of WVC against some threshold of concern (Wang et al. 2010). These approaches are complementary in that there may be interest in high-densities regardless of whether or not clustering is statistically significant; conversely there may be interest in identifying geographically-discreet areas for mitigation action.

Each highway was dissolved into one long line segment and subsequently cut into regular-length segments of 0.40 km (0.25 mi) to 1.6 km (1 mi). These lengths were chosen because of previous research indicating that these are appropriate road segment lengths for studying wildlife crossings and WVC (Malo et al. 2004; Taylor and Goldingay 2004). WVC observations were forced into co-location with their respective highways using a “snap to line” tool (<https://github.com/robintw/RTWTtoolsForArcGIS>) implemented in ArcGIS 10.1. The “spatial join” tool in ArcGIS 10.1 was used to sum the number of observations per line segment and these sums per line segment length were used as the basis for density-based analyses and for subsequent spatial autocorrelation analysis.

Number of hotspots in California and Maine

We used a measure of spatial autocorrelation test called the Getis-Ord G_i^* z-score statistic (Getis and Ord 1992) to determine whether or not WVC observations in California and Maine were spatially clustered in “hotspots” along highways. The Getis-Ord G_i^* z-score is a measure of the statistical significance of clustering for each analysis unit, in this case highway segments. The Getis-Ord G_i^* z-score was calculated using the default settings in ArcGIS 10.1.

Hotspot locations and spatial and temporal scales

Highway-specific observations were separated by year of observation, for full years of data: 2010, 2011, 2012, and 2013. Spatial autocorrelation of observations was determined for each year of observations. Different lengths of highway segment can affect where hotspots are identified. Shorter segment lengths (e.g., 0.4 km) may result in more hotspots than longer segments (e.g., 1.6 km) because there is greater likelihood at shorter distances that there will be a difference among segments in terms of # carcasses than at greater distances. The potential effect of varying highway segment lengths on hotspot identification was analyzed by carrying out autocorrelation analysis with 3 segment lengths: 0.4, 0.8 and 1.6 km.

Comparison of state agency and volunteer-collected data

Caltrans WVC data were used separately from volunteer-collected data from the California Roadkill Observation System (CROS) to analyze spatial autocorrelation and

carcass density. Mule deer (*Odocoileus hemionus*) comprised >95% of Caltrans observations for many highways and were selected from all Caltrans data (carcass retrievals and collisions) to determine density of deer-vehicle-collisions (DVC) along select highways.

Cost of deer-vehicle collisions

We also used estimates of the total cost of deer-vehicle collisions to provide estimates of the cost per mile segment per year from deer-vehicle collisions (Hujser et al. 2009). Deer-vehicle collision data were from both Caltrans and CROS databases and were summarized to the tenth post-mile. There are various costs associated with a collision between a deer and a vehicle. On average, a collision with a deer costs US\$6,671 (Hujser et al. 2009). We used this estimate of the total cost of DVC and segment-specific densities of DVC to provide estimates of the cost per mile segment per year from DVC. This provides another way to prioritize areas for mitigation, including both spatial location and economic benefits from mitigation action.

Results

Number of hotspots in California and Maine

The total number and length of statistically-significant clusters ($p < 0.05$), or “hotspots”, were determined for highways and interstates in each of California and Maine (Table 1, Figure 1). Twenty-eight percent (6,940 km) of California’s 25,041 km of state highways and interstates and 9% (947 km) of Maine’s 10,900 km of state highways and interstates were analyzed for hotspots, though not all highways had WVC observations along their entire length. The length of individual hotspots varied considerably, from 0.8 km to 17.7 km. The total length of all hotspots increased significantly with length of highway analyzed ($p < 0.02$) at a rate of 10%, 0.10 km/km (Figure 2). If this rate held for all highways, the total length of hotspots would be 2,504 km in California and 1,090 km in Maine.

Hotspot locations and spatial and temporal scales

A few highways had sufficient data to conduct year-specific cluster analysis for 2010, 2011, 2012, and 2013. For one example highway, CA-49, certain hotspots persisted throughout the 4 years of data collection (Figure 3A) and the majority were present in one or several years (Figure 3A). For another highway, CA-13, locations of hotspots varied from year to year (Figure 3B). One example highway (CA-190) was segmented into varying-lengths for analysis, from 0.40 km to 1.6 km (Figure 3C). There was a tendency for shorter segments to result in a greater number of identified statistically-

Table 1. Statistically-significant clusters (“hotspots”, $p < 0.05$) of dead animals (California, CA) and live and dead animals (Maine, ME) along state highways and interstates. The # of distinct hotspots and the total length of hotspots were determined for each highway.

Highway (length analyzed, km)	# observations/ observers	# observations/km	#/km Hotspots
CA-5 (1,283)	1,441/58	1.16	42/87
CA-50 (109)	415/18	3.81	7/42
CA-280 (39)	380/14	9.74	1/3.2
CA-80 (328)	679/50	2.07	7/24
CA-101 (1,302)	1,677/92	1.29	8/103
CA-99 (669)	350/37	0.52	3/40
CA-1 (1,053)	722/50	0.69	6/203
CA-49 (473)	540/37	1.14	4/82
CA-37 (35)	266/21	7.60	3/4.8
CA-4 (306)	217/21	0.71	3/19
CA-20 (341)	481/20	1.41	2/11
CA-3 (233)	309/8	1.33	1/85
CA-580 (122)	335/25	2.75	2/5.6
CA-13 (14)	580/7	41.4	2/2.0
CA-17 (43)	68/13	1.58	1/4.8
CA-70 (290)	617/60	2.13	12/28
CA-94 (56)	899/7	16.1	1/11
CA-190 (209)	637/12	3.05	3/31
(6,940)	10,612/ND		97/760
ME-295 (87)	394/30	4.53	3/8.0
ME-127 (24)	95/3	3.96	2/2.4
ME-116 (69)	45/1	0.65	1/0.8
ME-111 (22)	33/3	1.50	1/0.8
ME-128 (21)	60/4	2.86	2/2.4
ME-139/202/100A (40)	293/5	7.33	2/4.0
ME-17/126 (23)	51/4	2.22	0/0
ME-2/7/9 (37)	79/7	2.14	2/1.6
ME-4/16 (87)	107/6	1.23	2/5.6
ME-1 (537)	295/47	0.55	2/127
(947)	1,452/ND		17/153

significant clusters (0.4 km: $n = 20$ clusters) and longer segments to result in fewer and longer clusters (1.6 km: $n = 4$ clusters). For many of the highways, the statistically significant hotspots often overlapped at these different scales.

Comparison of state agency and volunteer-collected data

The vast majority of Caltrans observations were of mule deer (*Odocoileus hemionus*). For example, during one reporting period along I-80 (1967 to 1992), there were observations of 906 mule deer, 5 black bear (*Ursus americanus*), 1 beaver (*Castor canadensis*) and

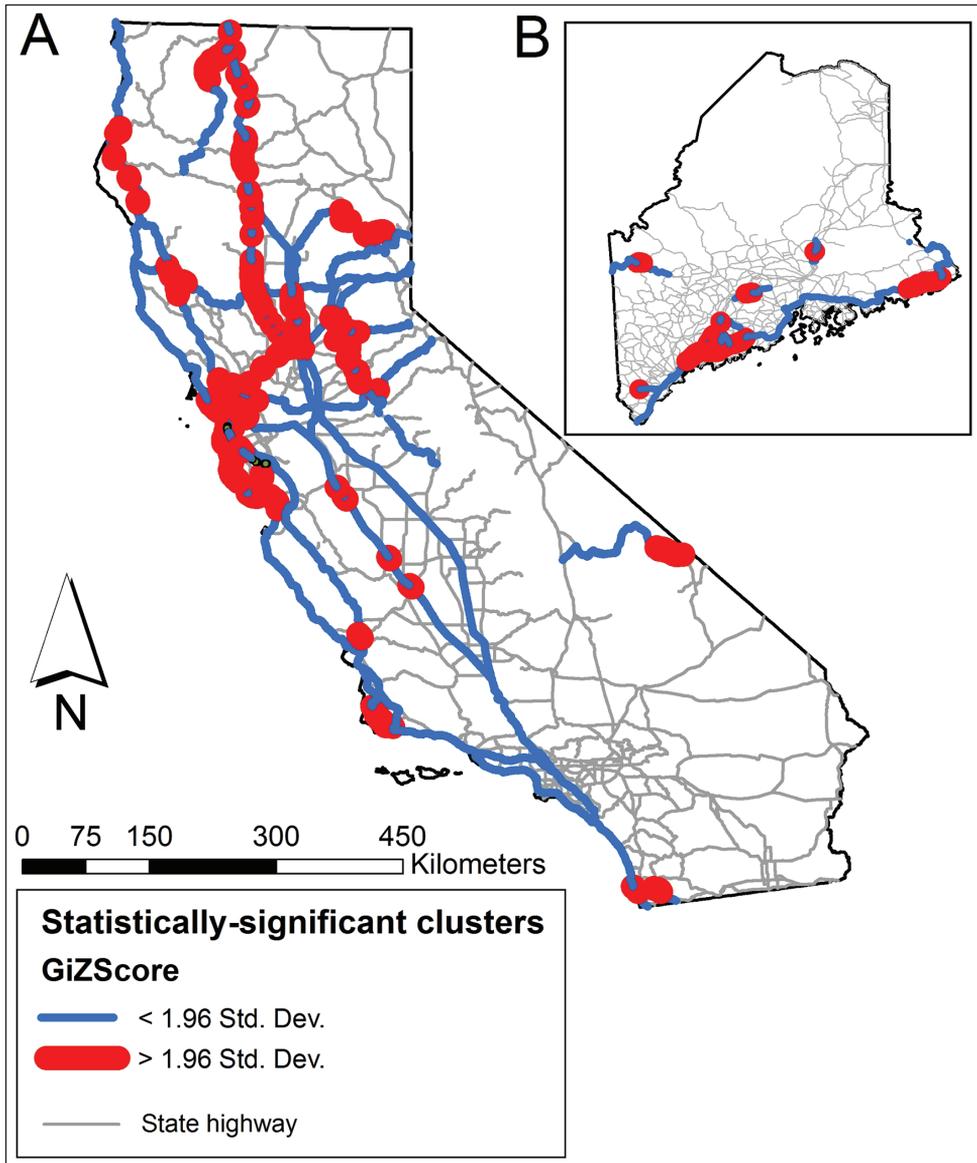


Figure 1. Locations of hotspots on California and Maine highways. The G_i^* statistic, Z-score indicates the statistical significance of WVC clusters. A score of >1.96 indicates a statistically-significant cluster ($p < 0.05$); scores lower than 1.96 are not significant ($p > 0.05$).

1 raccoon (*Procyon lotor*). This dominance of observations of deer is likely to be different for more urban areas. In comparison, observations from the CROS for I-80 (2009 to 2014) included 679 individuals from 63 species, with 69 individuals being mule deer. For the highways where state agency and volunteer-collected data were available, the carcass counts from each source for the most part did not overlap (Figure 4A, B). In other words,

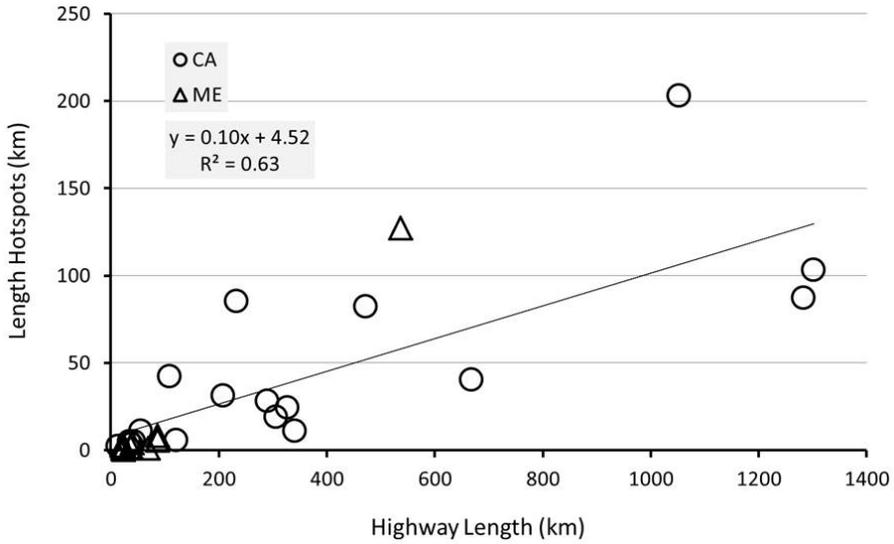


Figure 2. Relationship (CA and ME) between length of hotspots and highway length. The formulas and R^2 values are for the combined ME and CA data.

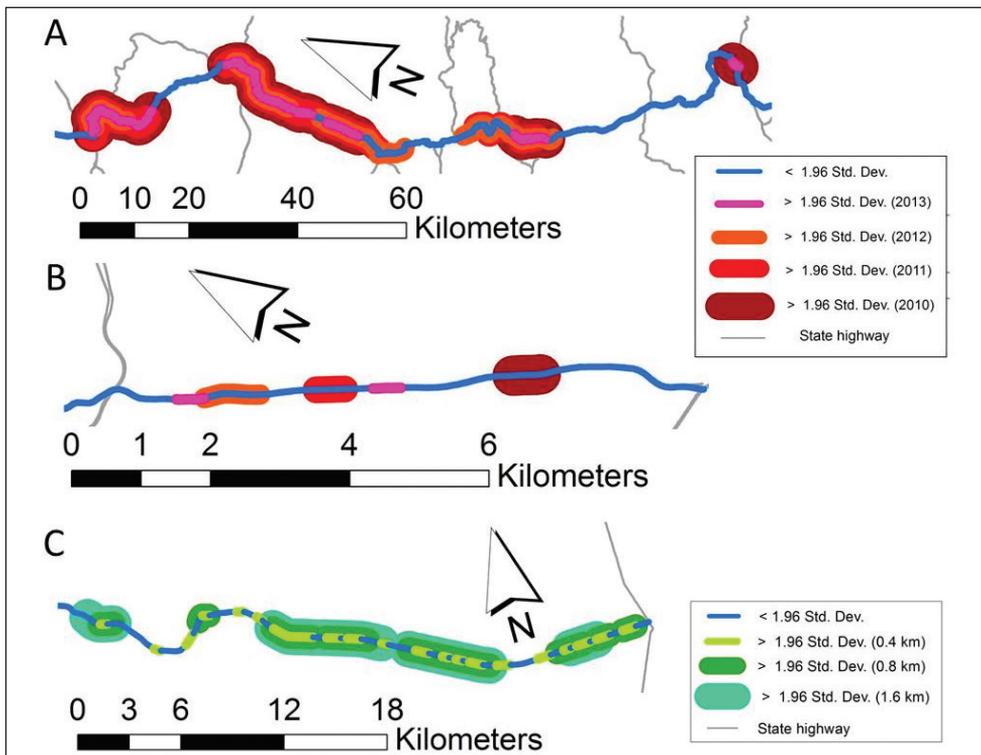


Figure 3. Geographic variation in hotspots among years and with varying highway-segment lengths. Annually-specific hotspots for **A** CA-49 and **B** CA-13 **C** Variation in position and number of hotspots along CA-190 with varying segment lengths: 0.4, 0.8, and 1.6 km segments.

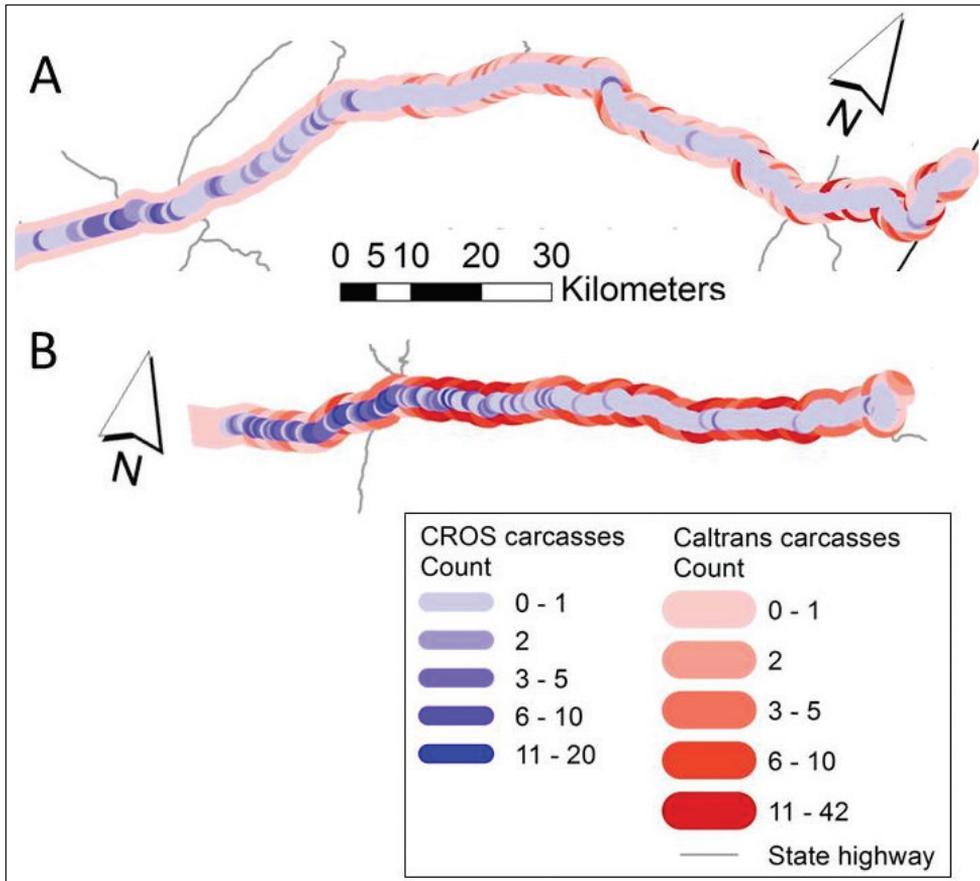


Figure 4. Comparison of state agency and volunteer-collected data-based hotspots. Carcasses reported in the CROS system (inner blue-range segments) overlaid with carcasses reported in the Caltrans system (outer red-range segments) along CA-80 (A) and along CA-50 (B).

where carcass counts from CROS were high, carcass counts from Caltrans were often low or nonexistent, and vice-versa. Similarly, the hotspots calculated using each source of data did not overlap with each other (Figure 4C, D). State agency data were dominated by mule deer carcasses, which were primarily collected at higher elevations and away from urban areas. Although data collection by volunteers also occurred in these areas, hotspots from their data were primarily identified near developed urban and agricultural areas.

Cost of Deer-Vehicle Collisions

Identifying locations of WVC clusters is one type of information useful for transportation mitigation planning. Identifying locations of high-cost from deer-vehicle collision (DVC) is another type. For one highway (CA-50), there was some overlap of hotspots

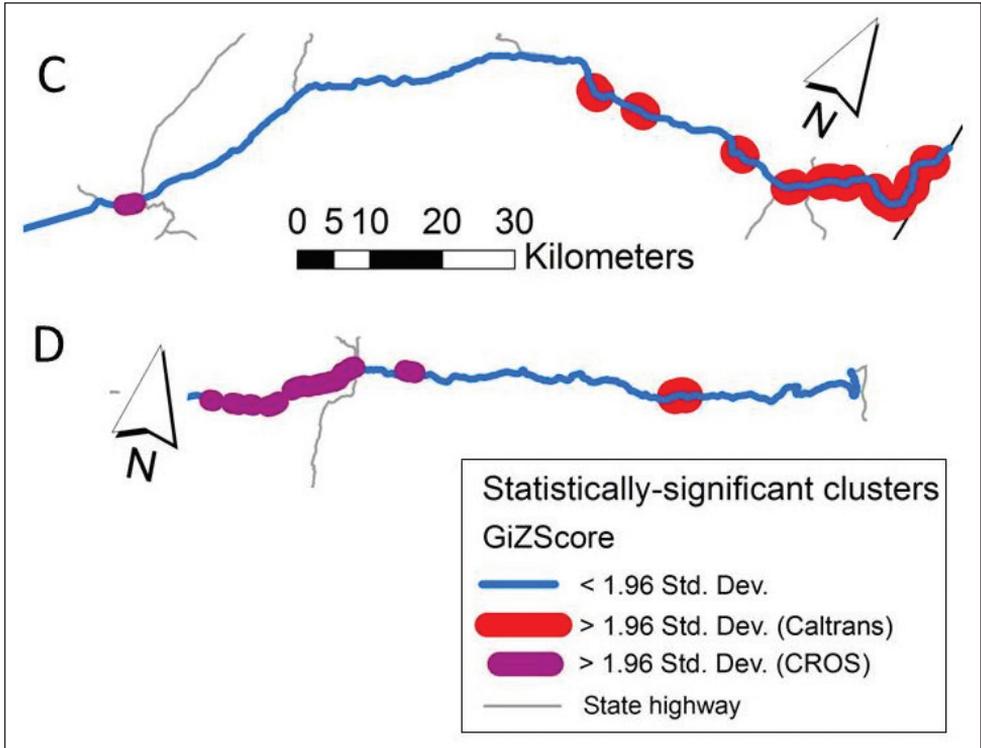


Figure 4. Continued. Locations of statistically-significant clusters from CROS data (purple segments) and Caltrans data (red segments) for CA-80 (C) and for CA-50 (D).

identified from volunteer observations of all species of WVC and 2 locations of high estimated cost of DVC from volunteer and DOT observations (Figure 5). For CA-50, the estimated annual cost of DVC ranged from <math>< \\$500</math> to $> \\$10,000$ per mile (Figure 5). For another highway (I-280), according to Caltrans databases, there have been 362 collisions with deer between January, 2005 and July, 2012, or roughly 48/year. For I-280, there was very little overlap between the single hotspot identified from volunteer observations and the longer stretches of high estimated annual cost from DVC (data not shown). Also, the estimated annual cost of DVC was higher than for SR 50, reflecting a higher rate of DVC, and varied from <math>< \\$1,000</math> to $> \\$40,000$ per mile.

Discussion

We demonstrate that volunteer observations of WVC from across a broad taxonomic range can be used in WVC hotspot identification on state highways. Within each of CA and ME, the systems described here represent the most extensive and taxonomically-broad wildlife monitoring effort, providing information about herpetofauna, birds, and

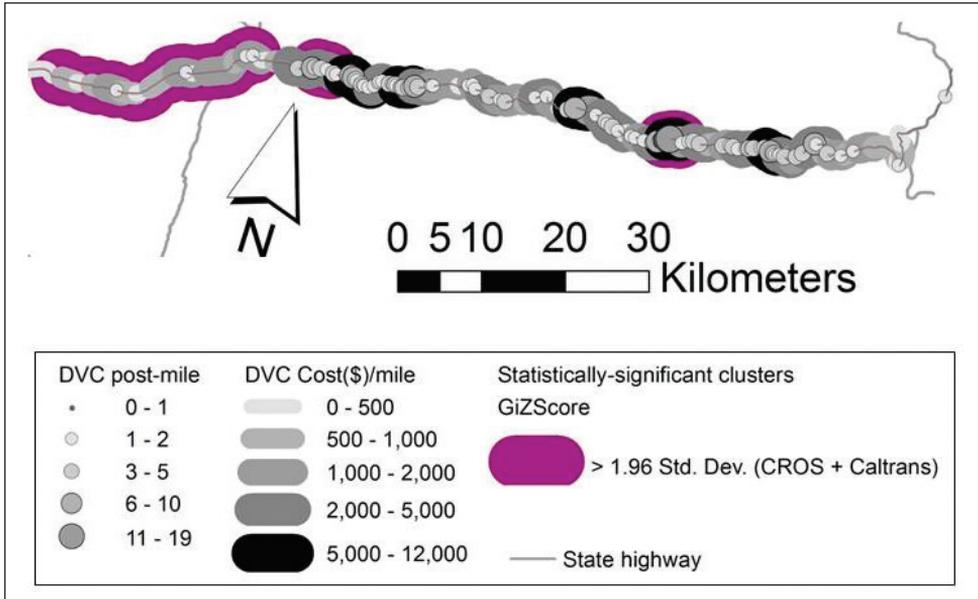


Figure 5. Locations of potential, cost-effective areas for mitigation. Statistically-significant clusters using volunteer observations (outer purple segments), annual rate of DVC per post-mile (points), and associated costs (\$/mile, gray segments) of DVC for CA-50.

mammals. The opportunistic wildlife observations in our systems may provide the raw data for statistical analyses of proximate contributors to wildlife-vehicle collisions and planning for minimizing WVC impacts on wildlife and drivers. Targeted surveys could be used to understand the impact of WVC on local wildlife populations, a critical need in understanding and mitigating transportation impacts (Fahrig and Rytwinski 2009).

We demonstrate here that a network of volunteer observers at the US state-scale provide information potentially-useful to DOTs in planning mitigation. In ME, records of all wildlife observations from 2012 were shared with Maine Audubon’s project partner the Maine Department of Transportation (MDOT) for use in their project scoping process (Maine Audubon, personal communication). Maine Audubon plans to continue annually to provide them with all observations as well as results from hotspot and density analysis (Maine Audubon, personal communication). The plan is to identify where areas of conservation concern overlap with MDOT projects in their 3-year plans. Where there is overlap through assessment of the habitats, species types, and road characteristics, projects can be designed to mitigate impacts to wildlife and public safety and enhance wildlife movement. In addition, locations of hotspots and high density of live and dead wildlife observations will be shared with local volunteer science volunteers for them to share and work with their towns planning and road departments for local road project mitigation. We hope that a similar DOT use of our hotspots analysis will also occur in California.

Wildlife-Vehicle Collisions

Animals die as result of collisions with vehicles because of traffic speed, traffic volumes, seasonal changes in movement, separation of important habitat areas, occluded line-of-sight, and other factors (Barthelmeß 2014; Hobday and Minstrell 2008; Litvaitis and Tash 2008). Most of the observations of dead animals made using the online, state systems described here were opportunistic and thus do not reflect actual rates of WVC on a particular roadway. For certain highways analyzed in the present study (CA-13, CA-190, CA-94, I-280) known observers have consistently and frequently made observations of WVC, thus in these cases the reported rates are a closer approximation of actual rates, especially for larger animals that are both easily observed and more difficult for scavengers to displace. WVC may occur and not be observed, be removed by highway maintenance crews, or be scavenged by other animals. Scavenging rates can be very high for roadkilled animals, affecting confidence in estimates of total impact of WVC on populations (Antworth et al. 2005; Barthelmeß and Brooks 2010).

The observations in the current study do reflect the presence of particular species at particular times of year and thus are a presence-only type of record. These data are useful in understanding wildlife distribution and movement, and for roadkilled animals, proximate causes of the collision (Barthelmeß 2014) or, as demonstrated here for frequently-driven roads, spatial-aggregation of collisions. Large-extent databases of WVC observations provide a tool for developing and testing predictive models for contributing factors to WVC. Because of unevenness in sampling and the unknown level of effort going into opportunistic reporting in the systems described here, we are not in a position to rank risks to wildlife among highways. However on single routes with high and/or regular rates of observation, local hotspots (blind curves, riparian crossings) may be located and calibration made of observations per unit effort, relative visibility and reporting rates found for different species, and other bias-correction rates calculated.

Mitigation planning

We demonstrate that volunteer-observations of WVC can contribute to understanding locations of WVC clusters that could be suitable for mitigation action at US state scales. We found that the length of highway segments analyzed had an effect on the position and occurrence of clusters. This is similar to the finding for bird species richness, where geographic clustering was found to depend on analytical scale (Ma et al. 2012). Because of this, the best approach for mitigation planning would be to carry out cluster analyses for multiple segment lengths, depending on the taxonomic group or process of interest. Previous research indicates that road segment lengths of 0.4 to 1.6 km area appropriate for studying wildlife crossings and WVC (Malo et al. 2004; Taylor and Goldingay 2004). Representation of cluster locations across multiple segment length classes may indicate places of particular importance from a collision point of view. For future studies, it would be worth formalizing segment-analysis lengths that

reflect a combination of consideration of ecological processes (e.g., species-dependent movement distances) and transportation-planning (e.g., segment scales for planning).

Identifying locations of clusters of WVC is a common step preceding mitigation and conservation actions to protect wildlife from vehicle-caused mortality (e.g., Hobday and Minstrell 2008). In the present study, cluster locations were found to vary in position along study highways across years of observations. For one highway (CA-13), there was virtually no overlap among WVC clusters from year to year (2010 to 2013). For another highway (CA-49), there were locations where clusters were identified every year, from 2010 to 2013. There were also locations where clusters were identified during 1, 2, or 3 of the 4 years. It is likely that factors contributing to WVC, such as traffic volume and speed, land cover, and road characteristics, did not change significantly during the study period. This suggests that temporal-dependence of cluster-locations is related to changes in the behavior of individuals and species along these highways. In addition, locations of statistically-significant clusters are not the only locations for concern about WVC. Highways with high rates of WVC across many adjacent segments may have few clusters, but many areas of concern because of impacts to drivers and animals (e.g., Figure 4, CA-50). This type of finding is very important for conservation planning, because it suggests that there may not be predictable landscape “corridors” or “linkages”, with corresponding stretches of highway suitable for mitigation action to protect wildlife movement. This finding contrasts with previous findings for certain taxonomic groups. For example, Langen et al. (2008) found that locations of clusters of herpetofauna road mortality were stable over time (i.e. comparison of 2002 and 2006/07). These clusters co-occurred with ponds and wetlands, which could explain the lack of change over time. We did not have sufficient data to divide the WVC observations into individual species and years.

The hotspots identified from volunteer-observations may not align with clusters identified using Department of Transportation (DOT)-collected WVC observations, because the latter are typically of ungulate and other large species that pose a risk to drivers. The combination of high-species-diversity observations by volunteers and DOT/wildlife agency observations of large animals could provide the ideal combination of WVC data to directly inform mitigation planning that provides both conservation and driver-safety benefits. In addition, because of the taxonomic breadth of volunteer-collected WVC observations, individual species could be considered for safety (e.g., mule deer) or conservation (e.g., meso-carnivores) reasons.

The annual cost of deer collisions, varied between the two CA state-highways analyzed and ranged from <US\$ 500 to >US\$30,000 per mile. To put these numbers in perspective, it can cost ~US\$25,000/mile to augment a 5-6 foot chain link fence to make it into an 8-foot, deer-resistant fence (e.g., deer-fence in ID, <https://fishandgame.idaho.gov/content/post/i-15-mule-deer-fence-near-pocatello-complete>) and up to US\$100,000/mile to construct a new 8-foot, deer-resistant fence. Fences are typically associated with purpose-built crossing, or other, structures that allow wildlife passage across a right-of-way. There were segments of high costs from deer collisions

(>US\$5,000/mile-year) throughout both SR 50 and I-280. Fence/crossing mitigation of certain stretches of state highway could pay for themselves in terms of avoided costs from deer collisions in a matter of 1–20 years, depending on rate of collision and existing fence infrastructure.

Many segments of the state highways studied are likely to have collisions between vehicles and any animal, including deer. These areas may or may not be predictable, but what is certainly predictable is that providing directional fencing to encourage deer and other wildlife to usable crossing structures will reduce WVC. Directional fencing and accompanying escape structures (e.g., jump-outs to allow animal escape from the road-side of a fence) and highway under or over-crossings have proven to be effective for reducing collisions between wildlife and vehicles (Hedlund et al. 2004; Seamans and Helon 2008). This utility is predictably compromised if the structures and materials are not monitored and maintained causing more animals to enter the roadways. At the scale of whole states and state highways, these structures will seem expensive, though not compared with the costs in lives, injury and property damage from collisions, or swerving to avoid collisions, with animals. Thus, strategically placing mitigation structures and showing their potential and actual cost-effectiveness will be very important for a more wide-spread adoption.

Acknowledgments

The authors would like to thank Barbara Charry of Maine Audubon for her suggestions and contributions to the Maine observation site and to Maine Audubon and Together Green for partial funding for development of the Maine web-site. The I-280 project cited was supported by agreement 04A3757 between the University of California, Davis and Caltrans. The remaining effort was contributed by the authors and volunteer wildlife-observers. The authors give a special thanks to Dr. Doug Long of the Oakland Museum of California for his many roadkill observations and his help with species-identity verification. The authors would also like to thank the volunteer observers who have contributed observations to the project. Finally, we appreciate the detailed comments from 2 reviewers who improved the manuscript. The authors have no conflict of interest related to this study.

References

- Antworth RL, Pikem DA, Stevens EE (2005) Hit and run: Effects of scavenging on estimates of roadkilled vertebrates. *Southeastern Naturalist* 4(4): 647–656. doi: 10.1656/1528-7092(2005)004[0647:HAREOS]2.0.CO;2
- Ball W, LeFevre S, Jarup L, Beale L (2008) Comparison of different methods for spatial analysis of cancer data in Utah. *Environmental Health Perspectives* 116(8): 1120–124. doi: 10.1289/ehp.10815

- Bang C, Faeth SH (2011) Variation in arthropod communities in response to urbanization: seven years of arthropod monitoring in a desert city. *Landscape and Urban Planning* 103: 383–399. doi: 10.1016/j.landurbplan.2011.08.013
- Barthelme EL, Brooks MS (2010) The influence of body-size and diet on road-kill trends in mammals. *Biodiversity Conservation* 19: 1611–1629. doi: 10.1007/s10531-010-9791-3
- Barthelme EL (2014) Spatial distribution of road-kills and factors influencing road mortality for mammals in Northern New York State. *Biodiversity and Conservation* 23: 2491–2514. doi: 10.1007/s10531-014-0734-2
- Beaudry F, Demaynadier PG, Hunter ML Jr. (2010) Identifying hot moments in road-mortality risk for freshwater turtles. *Journal of Wildlife Management* 74(1): 152–159. doi: 10.2193/2008-370
- Bil M, Andrasik R, Janozka Z (2013) Identification of hazardous road locations of traffic accidents by means of kernel density estimation and cluster significance evaluation. *Accident Analysis & Prevention* 55(0): 265–273. doi: 10.1016/j.aap.2013.03.003
- Bissonette JA, Kassar CA, Cook LJ (2008) Assessment of costs associated with deer-vehicle collisions: human death and injury, vehicle damage, and deer loss. *Human Wildlife Conflicts* 2: 17–27.
- Bonney R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg KV, Shirk J (2009) Citizen science: a developing tool for expanding science knowledge and scientific literacy. *BioScience* 59: 977–984. doi: 10.1525/bio.2009.59.11.9
- Conrad CC, Hillechey KG (2010) A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment*. doi: 10.1007/s10661-010-1582-5
- Cooper CB, Dickinson J, Phillips T, Bonney R (2007) Citizen science as a tool for conservation in residential ecosystems. *Ecology and Society* 12(1): 11. <http://www.ecologyandsociety.org/vol12/iss2/art11/>
- Cooper CB, Shirk J, Zuckerberg B (2014) The invisible prevalence of citizen science in global research: migratory birds and climate change. *PLoS ONE* 9: e106508. doi: 10.1371/journal.pone.0106508
- Corona P, Chirici G, McRoberts RE, Winter S, Barbati A (2011) Contribution of large-scale forest inventories to biodiversity assessment and monitoring. *Forest Ecology and Management* 262: 2061–2069. doi: 10.1016/j.foreco.2011.08.044
- Danks ZD, Porter WF (2010) Habitat characteristics of moose-vehicle collisions in western Maine. *Journal of Wildlife Management* 74(6): 1229–1241.
- Davis AK, Howard E (2005) Spring recolonization rate of monarch butterflies in eastern North America: new estimates from citizen-science data. *Journal of the Lepidopterists' Society* 59(1): 1–5.
- Delaney DG, Sperling CD, Adams CS, Leung B (2008) Marine invasive species: validation of citizen science and implications for national monitoring networks. *Biological Invasions* 10: 117–128. doi: 10.1007/s10530-007-9114-0
- Devictor V, Whittaker RJ, Beltrame C (2010) Beyond scarcity: citizen science programmes as useful tools for conservation biogeography. *Diversity & Distribution* 16: 354–362. doi: 10.1111/j.1472-4642.2009.00615.x

- Fahrig L, Rytwinski T (2009) Effects of roads on animal abundance: An empirical review and synthesis. *Ecology and Society* 14(1): 21. <http://www.ecologyandsociety.org/vol14/iss1/art21/>
- Fore LS, Paulsen K, O’Laughlin K (2001) Assessing the performance of volunteers in monitoring streams. *Freshwater Biology* 46: 109–123. doi: 10.1111/j.1365-2427.2001.00640.x
- George L, Macpherson JL, Balmforth Z, Bright PW (2011) Using the dead to monitor the living: Can road kill counts detect trends in mammal abundance? *Applied Ecology and Environmental Research* 9: 27–41. doi: 10.15666/aecr/0901_027041
- Getis A, Ord JK (1992) The analysis of spatial association by use of distance statistics. *Geographical Analysis* 24(3): 189–206. doi: 10.1111/j.1538-4632.1992.tb00261.x
- Goodchild MF (2007) Citizens as sensors: the world of volunteered geography. *GeoJournal* 69(4): 211–221. doi: 10.1007/s10708-007-9111-y
- Gunson KE, Clevenger AP, Ford AT, Bissonette JA, Hardy A (2009) A comparison of data sets varying in spatial accuracy used to predict the occurrence of wildlife-vehicle collisions. *Environmental Management* 44: 268–277. doi: 10.1007/s00267-009-9303-y
- Gunson KE, Mountrakis G, Quackenbush LJ (2011) Spatial wildlife-vehicle collision models: A review of current work and its application to transportation mitigation projects. *Journal of Environmental Management* 92: 1074–1082. doi: 10.1016/j.jenvman.2010.11.027
- Hampton SE, Strasser CA, Tewksbury JJ, Gram WK, Budden AE, Batcheller AL, Duke CS, Porter JH (2013) Big data and the future of ecology. *Frontiers in Ecology & Environment* 11(3): 156–162. doi: 10.1890/120103
- Hedlund JH, Curtis PC, Curtis G, Williams AF (2004) Methods to reduce traffic crashes involving deer: what works and what does not. *Traffic Injury Prevention* 5: 122–131. doi: 10.1080/15389580490435079
- Hobday AJ, Minstrell ML (2008) Distribution and abundance of roadkill on Tasmanian highways: human management options. *Wildlife Research* 35: 712–726. doi: 10.1071/WR08067
- Horsburgh JS, Tarboton DG, Piasecki M, Maidment DR, Zaslavsky I, Valentine D, Whitenack T (2009) An integrated system for publishing environmental observations data. *Environmental Modelling and Software* 24: 879–888. doi: 10.1016/j.envsoft.2009.01.002
- Huijser MP, Duffield JW, Clevenger AP, Ament RJ, McGowen PT (2009) Cost-benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: a decision support tool. *Ecology and Society* 14(2): 15. <http://www.ecologyandsociety.org/vol14/iss2/art15/>
- Kinley TA, Newhouse NJ (2009) Badger roadkill risk in relation to the presence of culverts and jersey barriers. *Northwest Science* 83(2): 148–153. doi: 10.3955/046.083.0206
- Kremen C, Ullmann KS, Thorp RW (2011) Evaluating the quality of citizen-scientist data on pollinator communities. *Conservation Biology* 25(3): 607–617. doi: 10.1111/j.1523-1739.2011.01657.x
- Langen TA, Ogden KM, Schwarting LL (2009) Predicting hot spots of herpetofauna road mortality along highway networks. *Journal of Wildlife Management* 73: 104–114. doi: 10.2193/2008-017

- Lee T, Quinn MS, Duke D (2006) Citizen, science, highways, and wildlife: Using a web-based GIS to engage citizens in collecting wildlife information. *Ecology and Society* 11(1). <http://www.ecologyandsociety.org/vol11/iss1/art11/>
- Litvaitis JL, Tash JP (2008) An approach toward understanding wildlife-vehicle collisions. *Environmental Management* 42: 688–697. doi: 10.1007/s00267-008-9108-4
- Loss SR, Will T, Marra PP (2014) Estimation of bird-vehicle collision mortality on US roads. *Journal of Wildlife Management* 78.5: 763–771. doi: 10.1002/jwmg.721
- Ma Z, Zuckerberg B, Porter WF, Zhang L (2012) Use of localized descriptive statistics for exploring the spatial pattern changes of bird species richness at multiple scales. *Applied Geography* 32: 185–194. doi: 10.1016/j.apgeog.2011.05.005
- Malo JE, Suárez F, Díez A (2004) Can we mitigate animal–vehicle accidents using predictive models? *Journal of Applied Ecology* 41: 701–710. doi: 10.1111/j.0021-8901.2004.00929.x
- Matos C, Sillero N, Argaña E (2012) Spatial analysis of amphibian road mortality levels in northern Portugal country roads. *Amphibia-Reptilia* 33: 469–483. doi: 10.1163/15685381-00002850
- Metzger KJ, Klaper R, Thomas MA (2011) Implications of informatics approaches in ecological research. *Ecological Informatics* 6: 4–12. doi: 10.1016/j.ecoinf.2010.11.003
- Nielsen CK, Anderson RG, Grund MD (2003) Landscape influences on deer-vehicle accident areas in an urban environment. *The Journal of Wildlife Management* 67(1): 46–51. doi: 10.2307/3803060
- Olson DD, Bissonnette JA, Cramer PC, Green AD, Davis ST, Jackson PJ, Coster DC (2014) Monitoring wildlife-vehicle collisions in the information age: How smartphones can improve data collection. *PLoS ONE* 9(6): e98613. doi: 10.1371/journal.pone.0098613
- Peterson AT, Vieglais DA (2001) Predicting species invasions using ecological niche modeling: New approaches from bioinformatics attack a pressing problem. *BioScience* 51(5): 363–701. doi: 10.1641/0006-3568(2001)051[0363:PSIUEN]2.0.CO;2
- Ryder TB, Reitsma R, Evans B, Marra PP (2010) Quantifying avian nest survival along an urbanization gradient using citizen- and scientist-generated data. *Ecological Applications* 20(2): 419–426. doi: 10.1890/09-0040.1
- Schmeller DS, Henry PY, Julliard R, Gruber B, Clobert J, Dziock F, Lengyel S, Nowicki P, De'ri E, Budrys E, Kull T, Tali K, Bauch B, Settele J, Van Swaay C, Kobler A, Babij V, Papastergiadou E, Henle K (2009) Advantages of volunteer-based biodiversity monitoring in Europe. *Conservation Biology* 23: 307–316. doi: 10.1111/j.1523-1739.2008.01125.x
- Seamans TW, Helon DA (2008) Evaluation of an electrified mat as a white-tailed deer (*Odocoileus virginianus*) barrier. *International Journal of Pest Management* 54(1): 89–94 doi: 10.1080/09670870701549624
- Silvertown J (2009) A new dawn for citizen science. *Trends in Ecology & Evolution* 24(9): 467–471. doi: 10.1016/j.tree.2009.03.017
- Somaweera R, Somaweera N, Shine R (2010) Frogs under friendly fire: How accurately can the general public recognize invasive species. *Biological Conservation* 143: 1477–1484. doi: 10.1016/j.biocon.2010.03.027

- Sullivan BL, Wood CL, Iliff MJ, Bonney RE, Fink D, Kelling S (2009) eBird: a citizen-based bird observation network in the biological sciences. *Biological Conservation* 142: 2282–2292. doi: 10.1016/j.biocon.2009.05.006
- Taylor BD, Goldingay RL (2004) Wildlife road-kills on three major roads in north-eastern New South Wales. *Wildlife Research* 31: 83–91. doi: 10.1071/WR01110
- Tillett BJ, Field IC, Bradshaw CJA, Johnson G, Buckworth RC, Meekan MG, Ovenden JR (2012) Accuracy rates of species identification by fisheries observers in a north Australian shark fishery. *Fisheries Research* 127–128: 109–115. doi: 10.1016/j.fishres.2012.04.007
- Wilson EO (1999) *The diversity of life*. First edition. Norton, New York, USA.
- Wilson S, Anderson EM, Wilson AS, Bertram DF, Arcese P (2013) Citizen science reveals an extensive shift in the winter distribution of migratory western grebes. *PLoS ONE* 8: e65408. doi: 10.1371/journal.pone.0065408