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Authors

Shilling, Fraser M

Waetjen, David P

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2 Fraser Shilling
3 Department of Environmental Science and Policy
4 University of California, Davis CA 95616
5 530-752-7859; 530-752-3350 (fax)
6 fmshilling@ucdavis.edu
7 RH: Shilling and Waetjen WVC Hotspots Identified Using Large Scale Volunteer Data
8

9 **Wildlife-Vehicle Collision Observation Collection and Hotspot Identification at Large**

10 **Scales**

11

12 FRASER M. SHILLING¹, Department of Environmental Science and Policy, University of
13 California, One Shields Avenue, Davis CA 95616

14 DAVID P. WAETJEN, Department of Environmental Science and Policy, University of
15 California, One Shields Avenue, Davis CA 95616

16

17

18 1 - corresponding author, fmshilling@ucdavis.edu

19 **ABSTRACT** Highways provide commuter traffic and goods movement among regions and
20 cities through wild, protected areas. Wildlife-vehicle collisions (WVC) can occur frequently
21 when wildlife are present, impacting drivers and animals. Because collisions are often avoidable
22 with constructed mitigation and reduced speeds, transportation agencies often want to know

1 where they can act most effectively and what kinds of mitigation are cost-effective. For this
2 study, WVC occurrences were obtained from two sources: 1) highway agencies that monitor
3 carcass retrieval and disposal by agency maintenance staff and 2) opportunistic observations of
4 carcasses by participants in two statewide systems, the California Roadkill Observation System
5 (CROS; <http://wildlifecrossing.net/california>) and the Maine Audubon Wildlife Road Watch
6 (MAWRW; <http://wildlifecrossing.net/maine>). Between September, 2009 and December 31,
7 2014, >33,700 independent observations of >450 vertebrate species had been recorded in these
8 online, form-based informatics systems by >1,300 observers. We asked whether or not WVC
9 observations collected by these extensive, volunteer-science networks could be used to inform
10 transportation-mitigation planning. Cluster analyses of volunteer-observed WVC were
11 performed using spatial autocorrelation tests for parts or all of 34 state highways and interstates.
12 Statistically-significant WVC hotspots were modeled using the Getis-Ord G_i^* statistic. High
13 density locations of WVC, that were not necessarily hotspots, were also visualized. Statistically-
14 significant hotspots were identified along ~7,900 km of highways. These hotspots are shown to
15 vary in position from year to year. For highways with frequent deer-vehicle collisions, annual
16 costs from collisions ranged from (US)\$0 to >(US)\$30,000/km. Carcass clusters from volunteer
17 data had very little or no overlap with similar findings from agency-collected WVC data. We
18 show that volunteer-collection of WVC observations at US state-scales could be useful in
19 prioritizing mitigation action by state transportation agencies to protect biodiversity and driver
20 safety. Because of the extent and taxonomic accuracy at which volunteer observations can be
21 collected, these may be the most important source of data for transportation agencies to protect
22 drivers and wildlife.

1

2

3 **KEY WORDS** Transportation, Wildlife-Vehicle Collisions, Roadkill, Informatics, Citizen

4 Science, Wildlife Observation, Wildlife Movement

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7

1 INTRODUCTION

2

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

15

16 Monitoring biodiversity and investigating causes of changes in biodiversity allows society to
17 make decisions about conservation (Wilson, 1999; Devictor et al., 2010; Bang and Faeth, 2011;
18 Corona et al., 2011) and improve management of human-wildlife conflict. Volunteer-science
19 provides a large and robust pool of enthusiastic people interested in problem-solving and data
20 collection. Furthermore, volunteer-science has facilitated analysis of ecological processes
21 operating at broad spatial and temporal scales, far beyond the limit of traditional field studies

1 (Wilson et al. 2013). Some of the largest wildlife-observation systems in the world rely primarily
2 on volunteer effort to develop reliable, verified wildlife data (Schmeller et al. 2009; Ryder et al.
3 2010; Cooper et al. 2014). These volunteers are often professional biologists making wildlife
4 observations “on the side” and contributing these observations to various wildlife reporting
5 systems (e.g. California Roadkill Observation System, CROS). One perception of volunteer
6 science collected data is that they may suffer from observer bias and identification error (Cooper
7 et al. 2014). However, this has not often been the case, and inaccuracies may be outweighed by
8 the size of datasets available from volunteers (Schmeller et al. 2009; Ryder et al. 2010). As the
9 volunteer science movement becomes an industry, it is anticipated that data collection will
10 become more streamlined and standardized, with the volunteer scientist benefiting from the
11 knowledge that they have helped advance in a scientific field they are passionate about.
12 Informatics is a discipline that provides tools useful to collect, manage, and use diverse types of
13 data to support research and management. Conservation-oriented analysis of ecological data
14 collected by volunteers in standardized web-based informatics systems is a critical component of
15 feedback to volunteers and can be an effective use of the data.

16

17 **Volunteer and Agency Reporting of Road-Associated Wildlife**

18 Globally, there are dozens of web-based systems for reporting WVC. For example, the Swedish
19 National Wildlife Accident Council maintains a website for official reporting of accidents
20 involving animals (<http://www.viltolycka.se/hem/>). The system is operated by the Swedish
21 National Police, it is the largest agency-owned, WVC-reporting system in the world, with over

1 200,000 records of WVC in the last five years. Online reporting and data display has been in
2 place since 2010, but data are available back to 1985. The largest, longest-running system that
3 relies on volunteer-observers reporting any species is the California Roadkill Observation
4 System (CROS), maintained by the Road Ecology Center at the University of California-Davis
5 (<http://www.wildlifecrossing.net/california>). In the US, the Idaho Department of Fish and Game
6 operates the Idaho Fish and Wildlife Information System -IFWIS
7 (<https://fishandgame.idaho.gov/species/roadkill>). The system allows entry of observation of any
8 carcass resulting from WVC and as of 12/2014 had >22,000 records. Many have appeared over
9 the last five years and they vary in their specific purpose, taxonomic breadth, and use of social
10 networks for collecting data and outreach. A few use smartphone-based applications to facilitate
11 data entry from the field (Olson et al., 2014) and some use social media and communication tools
12 to receive observations (e.g., Project Splatter in the UK, <http://projectsplatter.co.uk/>). One
13 purpose of this study was to find out whether it is possible to use the data from web-based
14 informatics systems containing volunteer wildlife observations, to plan for WVC mitigation at
15 the scale of US states.

16

17 Existing WVC reporting systems can consist of tens of thousands of data points and represent a
18 potential source of “big data” for road ecology, community ecology, biodiversity mapping, and
19 other scientific/engineering disciplines. Big data refers to datasets that are large and usually
20 geographically extensive, and so require novel solutions for storage, analysis, processing and
21 visualization. At a global level WVC reporting systems provide the largest known, continuous
22 source of data on animal occurrence and distribution whilst also providing opportunities for
23 tissue sampling of genetics, disease, and other testing. Carefully structured informatics (i.e.

1 collection, management and sharing) systems for these observations facilitate analyses and other
2 uses of the data.

3

4 **Spatial Clustering of WVC**

5 One common finding with spatial analysis of WVC is that collisions are clustered, which often
6 leads to analysis of proximate causes of clustering for individual species (e.g., road or landscape
7 features; Gunson et al, 2011). One approach is to use previous collisions to develop predictive
8 landscape models to find “hotspots” (Nielsen et al., 2003; Langen et al., 2009; Gunson et al.,
9 2011), or seasonality models to find “hot moments” (Beaudry et al., 2010). This is often done for
10 ungulates because collisions with ungulates are both a conservation and safety concern (e.g.,
11 Danks and Porter, 2010). There are various costs associated with a collision between a deer and a
12 vehicle; on average, a collision with a deer costs \$6,671 to society (Hujser et al., 2009). This
13 approach means that WVC can be measured in terms of their cost to society, which can matter
14 regardless of clustering of WVC. Less well-studied than WVC clustering is the idea that for
15 broad taxonomic groups, “sheet flow” of animals may result in WVC everywhere and
16 statistically-significant clustering may only be found because of limitations in the study area, or
17 data collection. Although understanding clustering for individual species is important for each of
18 those species in each of its habitats and landscapes; for highway planning, it is also important to
19 understand whether or not and why there are patterns of WVC for most or all vertebrate fauna
20 present in an area.

21

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

11

12 We describe the use of data from state-scale, online observational networks for roadkill/wildlife
13 occurrences in California (CA) and Maine (ME). We used a spatial-autocorrelation test (Getis
14 Ord, Gi*) to determine the significance of WVC differences among neighboring roadway
15 segments. We found that there were sufficient data to identify statistically-significant "hotspots"
16 for many of the states' highways. We propose that novel online, volunteer-based systems like
17 these could be used to augment the efforts of state DOTs and wildlife agencies and help inform
18 location and type of mitigation actions.

19

20

1 METHODS

2

3 The two states were chosen for the availability of existing large-scale, online systems of
4 volunteer-collected WVC data. At the time of writing, both systems were being actively used.
5 The California Roadkill Observation System (CROS, <http://www.wildlifecrossing.net/california>)
6 was launched in August 2009 to allow volunteer scientists to record carcass observations on
7 California roads and highways. California has a population of more than 37 million people and
8 >499,000 km of roadways networked across 411,000 km² of varied land cover types, including
9 urban, agriculture, forests, grasslands, and desert. Of these roadways, 196,381 km are major
10 roads, and 25,041 km are highways. Eighteen example highways were chosen in CA for
11 geospatial analysis: interstates 5, 80, 280, and 580 and state routes (SR) 1, 3, 4, 13, 17, 20, 37,
12 49, 50, 70, 94, 99, 101, and 190. A similar system was developed in early 2010 for Maine, the
13 Maine Audubon Wildlife Road Watch (<http://www.wildlifecrossing.net/maine>), to allow
14 collection of both live and dead animal observations on and immediately adjacent to Maine's
15 roads and highways. Maine has a population of 1,328,000 people and >60,600 km of roads,
16 including 10,900 km of highways, across its 84,000 km² of forests, wetlands, agricultural areas
17 and townships. Parts or all of 16 example highways were chosen in ME for geospatial analysis:
18 interstate 29 and state routes 1, 2, 4, 7, 9, 16, 17, 100A, 111, 116, 126, 127, 128, 139, and 202.

19

20 WVC Data Collection

21 Volunteer-collected data were downloaded for each of ME and CA from their respective online
22 systems. Data ranges for ME were June, 2010 to November, 2014 and for CA August, 2009 to

1 October, 2014. WVC for specific highways were selected by hand based on their proximity to
2 the highway. Any question about which of adjacent roadways a WVC was co-located with was
3 resolved by referring to the WVC record, which includes a narrative description of the site of
4 observation.

5 Caltrans maintains databases for carcass retrieval by District maintenance staff and for deer-
6 vehicle-collisions (DVC) requiring a report and attendance by the California Highway Patrol.
7 Partially-complete data-sets were retrieved from Caltrans using a request under the California
8 Public Records Act. Data for portions of two Districts (3 & 4), were the most complete for
9 carcass retrieval and accident reporting. Carcass retrieval data for 1984-1997 and 2001-2009 and
10 DVC data for 2008-2010 were obtained for District 3, I-80 and SR50, and carcass/DVC data for
11 2005 – 2012 were obtained for District 4, I-280. DVC were summarized by tenth post-mile for
12 each highway.

13

14 **Transportation Management Nexus: WVC Hotspot Analysis**

15 Two types of “hotspot” analysis were conducted: a test for spatial autocorrelation, which
16 identifies highway segments statistically-different from their neighbors, and calculation of WVC-
17 density (# WVC/km-year), which allows comparison of WVC against some threshold of concern
18 (Wang et al., 2010).

19 Each highway was dissolved into one long line segment and subsequently cut into regular-length
20 segments of 0.25, 0.50, or 1.00 mile. These lengths were chosen because of previous research
21 indicating that these are appropriate road segment lengths for studying wildlife crossings and
22 WVC (Malo et al., 2004; Taylor and Goldingay, 2004). WVC observations were forced into co-

1 location with their respective highways using a “snap to line” tool
2 (<https://github.com/robintw/RTWToolsForArcGIS>) implemented in ArcGIS 10.1. The “spatial
3 join” tool in ArcGIS 10.1 was used to sum the number of observations per line segment and these
4 sums per line segment length were used as the basis for density-based analyses and for
5 subsequent spatial autocorrelation analysis.

6

7 **Number of hotspots in California and Maine**

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

13

14 **Hotspot locations and spatial and temporal scales**

15 Highway-specific observations were separated by year of observation, for full years of data:
16 2010, 2011, 2012, and 2013. Spatial autocorrelation of observations was determined for each
17 year of observations. Different lengths of highway segment can affect where hotspots are
18 identified. Shorter segment lengths (e.g., $1/10^{\text{th}}$ of a mile) may result in more hotspots than
19 longer segments (e.g., 1 mile) because there is greater likelihood at shorter distances that there
20 will be a difference between # carcasses averaged over segments than at greater distances. The

1 potential effect of varying highway segment lengths on hotspot identification was analyzed by
2 carrying out autocorrelation analysis with 3 segment lengths: 0.25, 0.50, and 1.0 miles.

3 **Comparison of state agency and volunteer-collected data**

4 Caltrans carcass and WVC data were used separately from volunteer-collected data from the
5 California Roadkill Observation System (CROS) to analyze spatial autocorrelation and carcass
6 density. Mule deer comprised >95% of Caltrans observations for many highways and were
7 selected from all Caltrans data (carcass retrievals and collisions) to determine density of deer-
8 vehicle-collisions (DVC) along select highways.

9 **Cost of Deer-Vehicle Collisions**

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

18

1 RESULTS

2

3 **Number of hotspots in California and Maine**

4 The total number and length of hotspots were determined for highways and interstates in each of
5 California and Maine (Table 1). Twenty-eight percent (6,940 km) of California's 25,041 km of
6 state highways and interstates and 9% (947 km) of Maine's 10,900 km of state highways and
7 interstates were analyzed for hotspots. The length of individual hotspots varied considerably,
8 from 0.8 km to 17.7 km. The length of hotspots increased linearly with length of highway
9 analyzed at a rate of 10%, 0.10 km/km (Figure 2). If this rate held for all highways, the total
10 length of hotspots would be 2,504 km in California and 1,090 km in Maine.

11

12 **Hotspot locations and spatial and temporal scales**

13 A few highways had sufficient data to conduct year-specific cluster analysis for 2010, 2011,
14 2012, and 2013. For two example highways, CA-13 and CA-49, certain hotspots persisted
15 throughout the 5-years of data collection (Figure 3A,B). The majority were present in one or
16 several years, but not every year. One example highway (CA-190) was segmented into varying-
17 lengths for analysis, from 0.40 km (0.25 mi) to 1.6 km (1 mi). There was a tendency for shorter
18 segments to result in a greater number of identified statistically-significant clusters and longer
19 segments to result in fewer and longer clusters. For many of the highways, the statistically

1 significant hotspots often overlapped at these different scales. For CA-190, there were 14
2 hotspots at 0.40 km, 6 hotspots at 0.8 km, and 4 hotspots at 1.6 km (Figure 3C).

3

4 **Comparison of state agency and volunteer-collected data**

5 The vast majority of Caltrans observations were of mule deer. For example, during one reporting
6 period along I-80 (1967 to 1992), there were observations of 906 mule deer, 5 black bear, 1
7 beaver and 1 raccoon. This dominance of observations by deer is likely to be different for more
8 urban areas. In comparison, observations from the CROS for I-80 (2009 to 2014) included 679
9 individuals from 63 species, with 69 being mule deer. For the highways where state agency and
10 volunteer-collected data were available, the carcass counts and the hotspots calculated from each
11 source of data did not overlap (Figure 4). State agency data were dominated by mule deer
12 carcasses, which were primarily collected at higher elevations and away from urban areas.
13 Although data collection by volunteers also occurred in these areas, hotspots from their data
14 were primarily identified near developed urban and agricultural areas.

15

16 **Cost of Deer-Vehicle Collisions**

17 Identifying locations of WVC clusters is one type of information useful for transportation
18 mitigation planning. Identifying locations of high-cost from deer-vehicle collision (DVC) is
19 another type. For one highway, I-280 (39 km), according to Caltrans databases (TSN and

1 IMMS), there have been 362 collisions with deer between January, 2005 and July, 2012, or
2 roughly 48/year. On CA-50, there was some overlap of hotspots identified from volunteer
3 observations of all species of WVC and a location of high estimated cost of DVC from volunteer
4 and DOT observations (Figure 5A). On I-280, there was very little overlap between the single
5 hotspot identified from volunteer observations and the longer stretches of high estimated cost
6 from DVC (Figure 5B). For SR 50, the estimated annual cost of DVC ranged from <\$500 to
7 >\$10,000 per km (Figure 5A). For I-280, the estimated cost of DVC was higher than for SR 50,
8 reflecting a higher rate of DVC, and varied from <\$1,000 to >\$30,000 per km (Figure 5B).

9

10 **DISCUSSION**

11 We demonstrate that volunteer observations of WVC from across a broad taxonomic range can
12 be used in WVC hotspot identification on state highways. Within each of CA and ME, the
13 systems described here represent the most extensive and taxonomically-broad wildlife
14 monitoring effort, providing information about herpetofauna, birds, and mammals. The
15 opportunistic wildlife observations in our systems may provide the raw data for statistical
16 analyses of proximate contributors to wildlife-vehicle collisions and planning for minimizing
17 WVC impacts on wildlife and drivers. Targeted surveys could be used to understand the impact
18 of WVC on local wildlife populations, a critical need in understanding and mitigating
19 transportation impacts (Fahrig and Rytwinski, 2009).

20

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

14

15 **Wildlife-Vehicle Collisions**

16 Animals die as result of collisions with vehicles because of traffic speed, traffic volumes,
17 seasonal changes in movement, separation of important habitat areas, occluded line-of-sight, and
18 other factors (Barthelmess, 2014; Hobday and Minstrell, 2008; Litvaitis and Tash, 2008). Most of
19 the observations of dead animals made using the online, state systems described here were
20 opportunistic and thus do not reflect actual rates of WVC on a particular roadway. WVC may
21 occur and not be observed, be removed by highway maintenance crews, or be scavenged by
22 other animals. Scavenging rates can be very high for roadkilled animals, affecting confidence in

1 estimates of total impact of WVC on populations (Antworth et al., 2005; Barthelmeß and
2 Brooks, 2010). The observations do reflect the presence of particular species at particular times
3 of year and thus are a presence-only type of record useful in understanding wildlife distribution
4 and movement, and for roadkilled animals, proximate causes of the collision (Barthelmeß, 2014)
5 or, as demonstrated here for frequently-driven roads, spatial-aggregation of collisions. Large-
6 extent databases of WVC observations provide a tool for developing and testing predictive
7 models for contributing factors to WVC. Because of unevenness in sampling and the unknown
8 level of effort going into opportunistic reporting in the systems described here, we are not in a
9 position to rank risks to wildlife among highways. However on single routes with high and/or
10 regular rates of observation, local hotspots (blind curves, riparian crossings) may be located and
11 calibration made of observations per unit effort, relative visibility and reporting rates found for
12 different species, and other bias-correction rates calculated.

13

14 **Mitigation Planning**

15 We demonstrate that volunteer-observations of WVC can contribute to understanding locations
16 of WVC clusters that could be suitable for mitigation action. These hotspots may not align with
17 clusters identified using Department of Transportation (DOT)-collected WVC observations,
18 because the latter are typically of ungulate and other large species. The combination of high-
19 species-diversity observations by volunteers and DOT/wildlife agency observations could
20 provide the ideal combination of WVC data to directly inform mitigation planning that provides
21 both conservation and driver-safety benefits.

1 The annual cost of deer collisions, varied between the two CA state-highways analyzed and
2 ranged from <\$US500 to >\$US30,000 per km. To put this number in perspective, it can cost
3 ~\$US15,000/km to augment a 5-6 foot chain link fence to make it into an 8-foot fence (e.g.,
4 deer-fence in ID, [https://fishandgame.idaho.gov/content/post/i-15-mule-deer-fence-near-](https://fishandgame.idaho.gov/content/post/i-15-mule-deer-fence-near-pocatello-complete)
5 [pocatello-complete](https://fishandgame.idaho.gov/content/post/i-15-mule-deer-fence-near-pocatello-complete)) and up to \$US70,000/km to construct a new 8-foot fence. Fences are
6 typically associated with purpose-built, or other structures that allow wildlife passage across a
7 right-of-way. There were segments of high costs from deer collisions (>\$US5,000) throughout
8 both SR 50 and I-280. Fence/crossing mitigation of certain stretches of state highway could pay
9 for themselves in terms of avoided costs from deer collisions in a matter of 1-20 years,
10 depending on rate of collision and existing fence infrastructure.

11

12 Many segments of the state highways studied are likely to have collisions between vehicles and
13 any animal, including deer. These areas may be predictable, but what is certainly predictable is
14 that providing directional fencing to encourage deer and other wildlife to usable crossing
15 structures will reduce WVC. Directional fencing and accompanying structures (e.g., jump-outs to
16 allow animal escape from the road-side of a fence) have proven to be effective for reducing
17 collisions between deer and vehicles. Directional fencing, electrified mats (Seamans and Helon,
18 2008), and under-crossings (Hedlund et al., 2004) can be very useful at reducing WVC. This
19 utility is predictably compromised if the structures and materials are not monitored and
20 maintained causing more animals to enter the roadways. At the scale of whole states and state
21 highways, these structures will seem expensive, thus placing them strategically, and showing
22 their potential and actual cost-effectiveness will be very important.

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11

12 LITERATURE CITED

- 13 Antworth, RL, Pikem DA, and Stevens EE (2005) Hit and run: Effects of scavenging on
14 estimates of roadkilled vertebrates. *Southeastern Naturalist* 4(4):647-656.
- 15 Bang, C and Faeth, SH (2011) Variation in arthropod communities in response to urbanization:
16 seven years of arthropod monitoring in a desert city. *Landscape and Urban Planning*
17 103:383-399.
- 18 Barthelmess, EL and Brooks, MS (2010) The influence of body-size and diet on road-kill trends
19 in mammals. *Biodiversity Conservation* 19:1611-1629.
- 20 Barthelmess, EL (2014) Spatial distribution of road-kills and factors influencing road mortality
21 for mammals in Northern New York State. *Biodiversity and Conservation* 23: 2491-2514.
- 22 Beaudry, F, Demaynadier PG, and Hunter ML Jr. (2010) Identifying hot moments in road-
23 mortality risk for freshwater turtles. *Journal of Wildlife Management*, 74 (1): 152-159.
- 24 Bissonette, JA, Kassar, CA, Cook LJ (2008) Assessment of costs associated with deer-vehicle
25 collisions: human death and injury, vehicle damage, and deer loss. *Human Wildlife*
26 *Conflicts* 2:17-27.
- 27 Bonney, R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg KV, and Shirk J (2009)
28 Citizen science: a developing tool for expanding science knowledge and scientific
29 literacy. *BioScience* 59:977-984.

- 1 Conrad CC, and Hilchey KG (2010) A review of citizen science and community-based
2 environmental monitoring: issues and opportunities. *Environmental Monitoring and*
3 *Assessment*. DOI 10.1007/s10661-010-1582-5.
- 4 Cooper CB, Dickinson J, Philips T, and Bonney R (2007) Citizen science as a tool for
5 conservation in residential ecosystems. *Ecology and Society* 12(1):11. [online] URL:
6 <http://www.ecologyandsociety.org/vol12/iss2/art11/>
- 7 Cooper CB, Shirk J, and Zuckerberg B (2014) The invisible prevalence of citizen science in
8 global research: migratory birds and climate change. *PloS one* 9: e106508.
- 9 Corona P, Chirici G, McRoberts RE, Winter S, and Barbarti A (2011) Contribution of large-scale
10 forest inventories to biodiversity assessment and monitoring. *Forest Ecology and*
11 *Management* 262:2061-2069.
- 12 Danks ZD and Porter WF (2010) Habitat characteristics of moose-vehicle collisions in western
13 Maine. *Journal of Wildlife Management*, 74(6): 1229–1241.
- 14 Davis AK and Howard E (2005) Spring recolonization rate of monarch butterflies in eastern
15 North America: new estimates from citizen-science data. *Journal of the Lepidopterists'*
16 *Society* 59(1):1-5
- 17 Delaney DG, Sperling CD, Adams CS, and Leung B (2008) Marine invasive species: validation
18 of citizen science and implications for national monitoring networks. *Biological*
19 *Invasions* 10:117-128.
- 20 Devictor V, Whittaker RJ, and Beltrame C (2010) Beyond scarcity: citizen science programmes
21 as useful tools for conservation biogeography. *Diversity & Distribution* 16:354-362.
- 22 Fahrig L and Rytwinski T (2009) Effects of roads on animal abundance: An empirical review
23 and synthesis. *Ecology and Society* 14(1) pp. 21. [online] URL:
24 <http://www.ecologyandsociety.org/vol14/iss1/art21/>
- 25 Fore LS, Paulsen K, and O’Laughlin K (2001) Assessing the performance of volunteers in
26 monitoring streams. *Freshwater Biology* 46:109–123.
- 27 George L, Macpherson JL, Balmforth Z, and Bright PW (2011) Using the dead to monitor the
28 living: Can road kill counts detect trends in mammal abundance? *Applied Ecology and*
29 *Environmental Research* 9: 27-41.
- 30 Getis A and Ord JK (1992) The analysis of spatial association by use of distance statistics.
31 *Geographical Analysis* 24(3):189-206.
- 32 Goodchild MF (2007) Citizens as sensors: the world of volunteered geography. *GeoJournal* 69
33 (4):211–221.
- 34 Gunson KE, Clevenger AP, Ford AT, Bissonette JA, and Hardy A (2009) A comparison of data
35 sets varying in spatial accuracy used to predict the occurrence of wildlife-vehicle
36 collisions. *Environmental Management* 44:268-277.
- 37 Gunson KE, Mountrakis G, and Quackenbush LJ (2011) Spatial wildlife-vehicle collision
38 models: A review of current work and its application to transportation mitigation
39 projects. *Journal of Environmental Management* 92: 1074-1082.
- 40 Hedlund JH, Curtis PC, Curtis G, and Williams AF (2004) Methods to reduce traffic crashes
41 involving deer: what works and what does not. *Traffic Injury Prevention* 5:122-131.
- 42 Hobday AJ and Minstrell ML (2008) Distribution and abundance of roadkill on Tasmanian
43 highways: human management options. *Wildlife Research* 35:712-726.

- 1 Horsburgh JS, Tarboton DG, Piasecki M, Maidment DR, Zaslavsky I, Valentine D, and
2 Whitenack T (2009) An integrated system for publishing environmental observations
3 data. *Environmental Modelling and Software* 24:879-888.
- 4 Huijser MP, Duffield JW, Clevenger AP, Ament RJ, and McGowen PT (2009) Cost-benefit
5 analyses of mitigation measures aimed at reducing collisions with large ungulates in the
6 United States and Canada: a decision support tool. *Ecology and Society*, 14(2): 15.
7 [online] URL: <http://www.ecologyandsociety.org/vol14/iss2/art15/>
- 8 Kinley TA, and Newhouse NJ (2009) Badger roadkill risk in relation to the presence of culverts
9 and jersey barriers. *Northwest Science* 83 (2):148–153.
- 10 Kremen C, Ullmann KS, and Thorp RW (2011) Evaluating the quality of citizen-scientist data on
11 pollinator communities. *Conservation Biology* 25(3):607-617.
- 12 Langen TA, Ogden KM, and Schwarting LL (2009) Predicting hot spots of herpetofauna road
13 mortality along highway networks. *Journal of Wildlife Management* **73**: 104-114.
- 14 Lee T, Quinn MS, and Duke D (2006) Citizen, science, highways, and wildlife: Using a web-
15 based GIS to engage citizens in collecting wildlife information. *Ecology and Society*
16 11(1) [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art11/>
- 17 Litvaitis JL, and Tash JP (2008) An approach toward understanding wildlife-vehicle collisions.
18 *Environmental Management* 42:688-697.
- 19 Loss SR, Will T, Marra PP (2014) Estimation of bird-vehicle collision mortality on US roads.
20 *Journal of Wildlife Management* 78.5: 763-771.
- 21 Malo JE, Suárez F, and Díez A (2004) Can we mitigate animal–vehicle accidents using
22 predictive models? *Journal of Applied Ecology* 41:701-710.
- 23 Matos C, Sillero N, and Argaña E (2012) Spatial analysis of amphibian road mortality levels in
24 northern Portugal country roads. *Amphibia-Reptilia* 33: 469-483.
- 25 Metzger KJ, Klaper R, and Thomas MA (2011) Implications of informatics approaches in
26 ecological research. *Ecological Informatics* 6: 4-12.
- 27 Nielsen CK, Anderson RG, and Grund MD (2003) Landscape influences on deer-vehicle
28 accident areas in an urban environment. *The Journal of Wildlife Management* 67(1): 46-
29 51
- 30 Olson DD, Bissonnette JA, Cramer PC, Green AD, Davis ST, Jackson PJ, Coster DC (2014)
31 Monitoring wildlife-vehicle collisions in the information age: How smartphones can
32 improve data collection. *PLoS ONE* 9(6): e98613. doi:10.1371/journal.pone.0098613
- 33 Peterson AT and Vieglais DA (2001) Predicting species invasions using ecological niche
34 modeling: New approaches from bioinformatics attack a pressing problem. *BioScience*
35 51(5):363-701
- 36 Ryder TB, Reitsma R, Evans B, and Marra PP (2010) Quantifying avian nest survival along an
37 urbanization gradient using citizen- and scientist-generated data. *Ecological Applications*
38 20(2):419-426.
- 39 Schmeller DS, Henry PY, Julliard R, Gruber B, Clobert J, Dziock F, Lengyel S, Nowicki P,
40 De´ri E, Budrys E, Kull T, Tali K, Bauch B, Settele J, Van Swaay C, Kobler A, Babij V,
41 Papastergiadou E, and Henle K (2009) Advantages of volunteer-based biodiversity
42 monitoring in Europe. *Conservation Biology* 23: 307–316.
- 43 Seamans TW and Helon DA (2008) Evaluation of an electrified mat as a white-tailed deer
44 (*Odocoileus virginianus*) barrier. *International Journal of Pest Management* 54(1): 89-94

- 1 Silvertown J (2009) A new dawn for citizen science. *Trends in Ecology & Evolution* 24 (9):467–
2 471.
- 3 Somaweera R, Somaweera N, and Shine R (2010) Frogs under friendly fire: How accurately can
4 the general public recognize invasive species. *Biological Conservation* 143: 1477-1484.
- 5 Sullivan BL, Wood CL, Iliff MJ, Bonney RE, Fink D, and Kelling S (2009) eBird: a citizen-
6 based bird observation network in the biological sciences. *Biological Conservation*
7 142:2282-2292
- 8 Taylor BD, and Goldingay RL (2004) Wildlife road-kills on three major roads in north-eastern
9 New South Wales. *Wildlife Research* 31:83-91.
- 10 Tillett BJ, Field IC, Bradshaw CJA, Johnson G, Buckworth RC, Meekan MG, and Ovenden JR
11 (2012) Accuracy rates of species identification by fisheries observers in a north
12 Australian shark fishery. *Fisheries Research*, 127-128:109-115.
- 13 Wilson EO (1999) *The diversity of life*. First edition. Norton, New York , USA.
- 14 Wilson S, Anderson EM, Wilson AS, Bertram DF, and Arcese P (2013) Citizen science reveals
15 an extensive shift in the winter distribution of migratory western grebes. *PloS One* 8:
16 e65408.

1 FIGURE LEGENDS

- 2 1. Locations of hotspots on California and Maine highways. The G_i^* statistic, Z-score
3 indicates the statistical significance of clusters of animal carcasses. A score of >1.96 indicates a
4 statistically-significant cluster; scores lower than 1.96 are not significant.
- 5 2. Relationship (CA and ME) between (A) number of observations and highway length and
6 (B) length of hotspots and highway length. The formulas and R^2 values are for the combined ME
7 and CA data.
- 8 3. Geographic variation in hotspots with time and segment length. Annually-specific hotspots
9 for (A) CA-13 and (B) CA-49. (C) Variation in position and extent of hotspots along CA-190
10 with varying segment lengths: 0.25, 0.5, and 1 mile segments.
- 11 4. Comparison of state agency and volunteer-collected data-based hotspots. A) Carcasses
12 reported in the CROS system (inner segments) overlaid with carcasses reported in the Caltrans
13 system (outer segments) along CA-80. B) Carcasses reported in the CROS system (inner
14 segments) overlaid with carcasses reported in the Caltrans system (outer segments) along CA-
15 49. The legend is the same for (A) and (B). C) Locations of statistically-significant clusters from
16 CROS data (inner segments) and Caltrans data (outer segments) for CA-80. D) Locations of
17 statistically-significant clusters from CROS data (inner segments) and Caltrans data (outer
18 segments) for CA-50. The legend is the same for (C) and (D).
- 19 5. Locations of potential, cost-effective areas for mitigation. A) Statistically-significant
20 clusters using volunteer observations (outer segments), rate of DVC per post-mile (points), and
21 associated costs (\$/mile) of DVC for CA-50. B) Statistically-significant clusters using volunteer
22 observations (outer segments), rate of DVC per post-mile (points), and associated costs (\$/mile)
23 of DVC for CA-280.
- 24

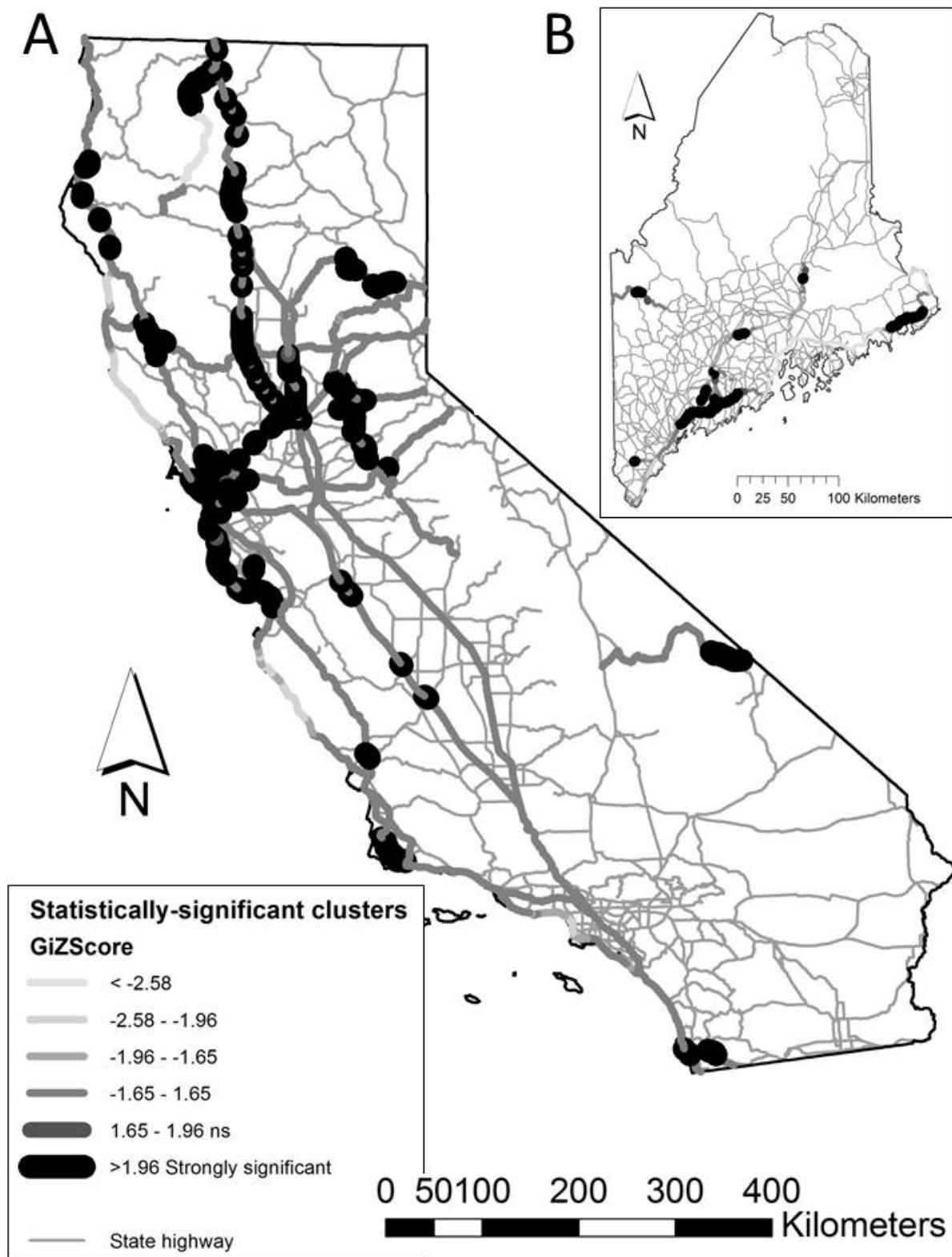
- 1 **Table 1:** Clusters (“hotspots”) of dead animals (California, CA) and live and dead animals
 2 (Maine, ME) along state highways and interstates. The # of distinct hotspots and the total length
 3 of hotspots were determined for each highway.

| Highway (length analyzed) | # 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 |

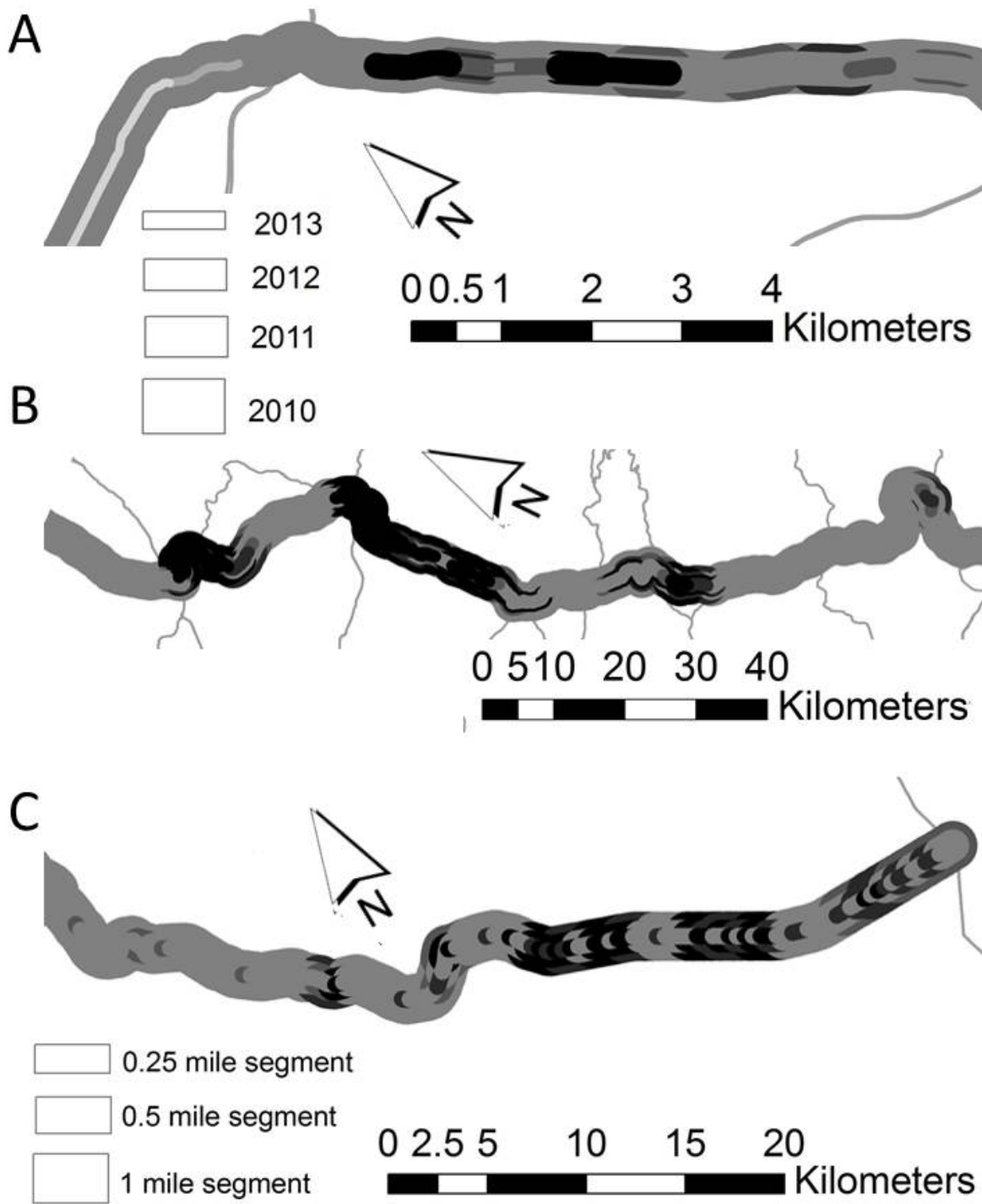
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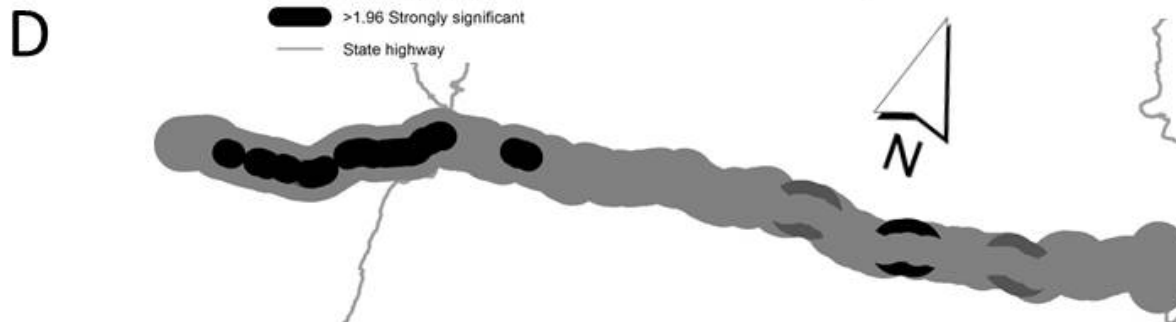
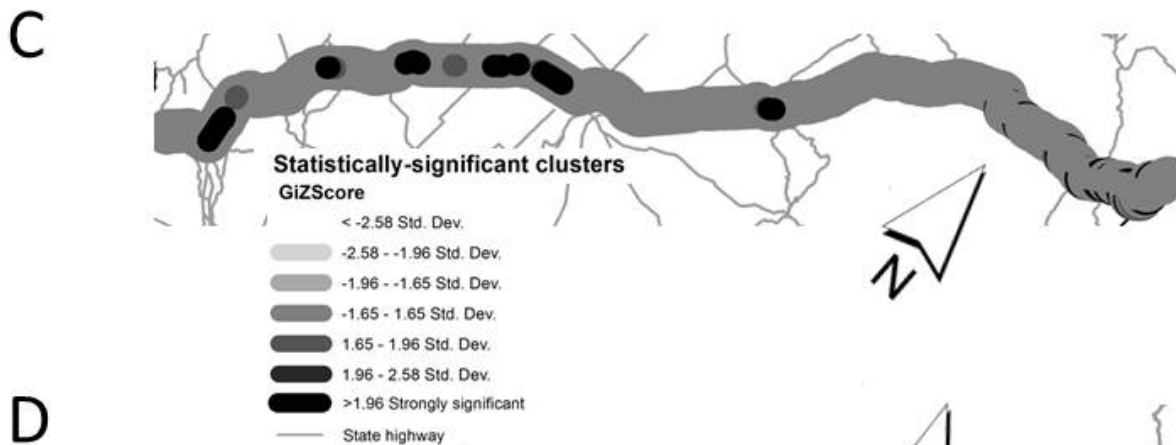
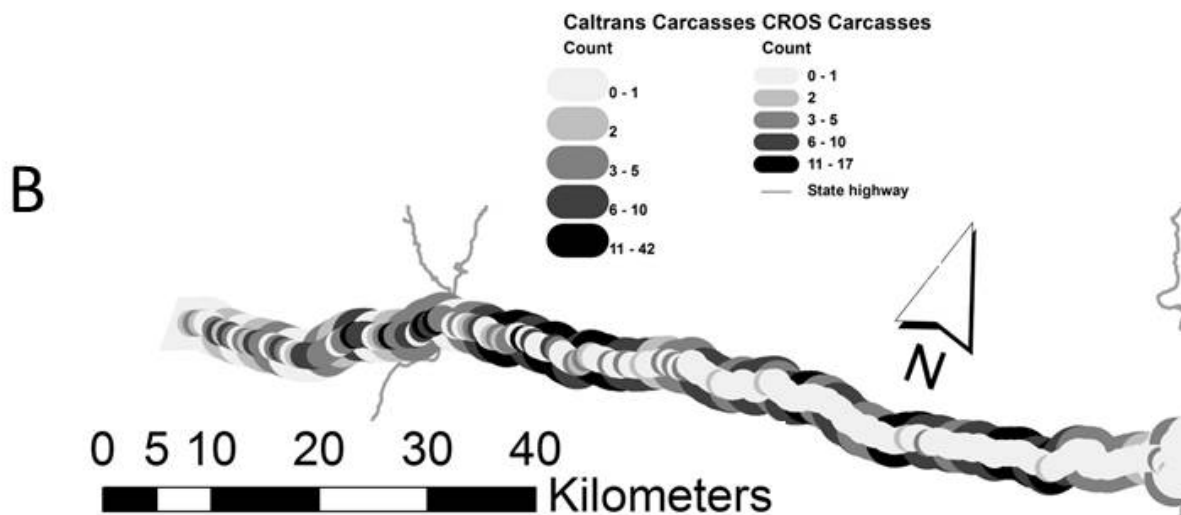
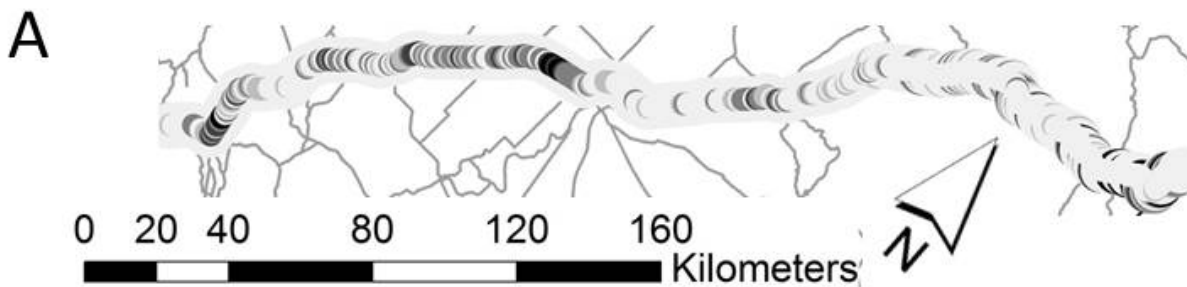
1 Figure 1



1 Figure 3



1 Figure 4



1 Figure 5

