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Review

Designing wildlife-vehicle conflict observation systems to inform ecology and transportation studies

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ABSTRACT

Globally, wildlife-vehicle conflict (WVC) fragments wildlife populations (due to road/traffic-aversion), kills and injures individual animals, can cause wildlife population declines, may eventually contribute to local or total extinction of certain species, and can harm vehicles and drivers. Preventing WVC begins with recording locations of conflict, such as vehicle crashes, animal carcasses (roadkill), or animal behavior around roads, such as avoidance of roads or crossing-behavior. These data are ideally used to inform transportation policy and planning and to retrofit roadways and their structures to reduce WVC. We are collectively involved with or manage eight regional or national systems for reporting WVC in collaboration with volunteers and/or agency staff. In this review, we survey systems for recording WVC by volunteers and agency staff at different geographical scales, based on existing literature and our personal experience. We report the range of data collection methods, data management systems and data visualizations employed as well as discuss the groups and type of volunteers and agencies involved. We use our expertise and the global survey to provide methodological specifications based on current best-practice for collecting and using WVC data to inform transportation and conservation decisions. We conclude with a vision of next steps toward a global network of WVC reporting systems, that have clear and practical applications for improved conservation research as well as guidelines for management of road networks.

1. Introduction

Currently, a fifth of the Earth's terrestrial surface is located within 1 km of a road (Ibisch et al., 2016), with an additional 25 million kilometers of roads projected to be built by 2030 (Leonard and Hochuli, 2017; Lawton, 2018) of which 90% are proposed for lower income countries (Dulac, 2013). Roads and other linear infrastructure (such as railways, power lines and pipelines) fragment natural and human communities and promise to do so for decades to come (Laurance et al., 2014; Brady and Richardson, 2017). They are inevitable requirements and products of modern economies, and for many Western countries (usually termed 'developed countries'), exist as networks to supply raw goods (Laurance et al., 2014). One of the most immediate and obvious negative impact of roads is wildlife-vehicle conflict (WVC), often thought of as carcasses on or beside roads (i.e. roadkill; Clevenger et al., 2003; Seo et al., 2015; Bíl et al., 2017). Because of both the visual impact of the carcasses and the opportunity they pro-

Abbreviations: WVC, wildlife vehicle conflict; CHIPs, California Highway Incident Reporting System; CROS, California Roadkill Observation System; AWW, Alberta Wildlife Watch; DOW, Dieren onder de wielen Natuurpunt; SZ, Srazenazver.cz Czech Republic; MAWRW, Maine Audubon Wildlife Road Watch; PR, Project Roadkill; PS, Project Splatter; RW, Road Watch; SPNI, Society for Protection of Nature in Israel; WI, Wildlife Incident.

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vide to collect data that can inform ecological and risk-mitigation studies, regional and national programs have developed over the last decade to record carcass presence (Santos et al., 2015; Tatewaki and Koike, 2018) and sometimes absence (Waetjen and Shilling, 2017; Collinson et al., 2019).

A WVC event can manifest in two forms; the first instance is when wildlife is too close to a roadway and either causes alarm for either (or both) the animal and the driver (Ruiz-Capillas et al., 2015) or in the second instance, and more extreme case, WVC can lead to the death and/or injury of both the driver and animal (Kumar, 2016). Typically, the definition and analysis of WVC focuses on just the collision event (for example, Rosell et al., 2013). For the purposes of our review, we define WVC here, as including the full spectrum; from alarm to death for either, or both, the animal and driver. Although not well-documented in the literature, this broad definition is supported by the authors' perception that there is an increasing awareness that conflict resulting from drivers who try to avoid a collision, or wildlife avoiding roadways, may lead to negative consequences. Furthermore, while WVC data collection generally centers around collisions and animal carcasses, studies of driver reactions to animals in the road and wildlife responses to roads and traffic (for example, aversion) suggests that a broader definition would be useful and can be incorporated into wider WVC studies by various data collection methodologies (see Collinson et al., 2014; Wolfe et al., 2019).

1.1. History of volunteer-involvement in WVC data collection

In the last decade, the time and effort cost of environmental monitoring (across all scientific disciplines) has resulted in a shift from government and academic entities to volunteer networks (Wilson et al., 2013). This has been especially true for global WVC reporting, and ad hoc volunteer-based data collection is increasingly addressing this gap (Shilling et al., 2015). Volunteer science, also known as crowd-sourced data-collection or citizen science (Louv and Fitzpatrick, 2012; Wilson et al., 2013; Heigl et al., 2019) provides a large and robust pool of enthusiastic people interested in problem solving and data collection. Volunteer networks may include managers and scientists from transportation and wildlife agencies, NGOs, colleges and universities and the general community all contributing by becoming involved in ecological research. Volunteer collection of natural history data already has a long history in certain domains (for example, Christmas Bird Count, begun in 1900; Droege, 2007 or Miller-Rushing et al., 2012 or Strasser et al., 2019). Within biodiversity research alone, the effort contributed by volunteers across 388 projects worldwide included 1.3 million people and an equivalent in-kind effort worth US$2.5 billion (Theobald et al., 2015).

The rapid expansion of volunteer involvement in environmental monitoring over the last decade, including WVC reporting, has led to concerns about: data quality (Conrad and Hilchey, 2011; Aceves-Bueno et al., 2017), roles of the observers (Cooper and Lewenstein, 2016; Ceccaroni et al., 2017), terminology to describe the activity (Eitzel et al., 2017; Heigl et al., 2019), use of the information collected and its use in decision-making (Newman et al., 2017), uneven representation of taxa in global biodiversity monitoring (Chandler et al., 2017), uneven representation of taxa among volunteer types (Bíl et al., 2020) and intellectual property of the data (Guerrini et al., 2018). Assuming these issues can be resolved successfully and given the massive extent of road-networks and WVC, volunteer-collection of WVC data could be an important source of ecological information for governments, academia, and the public (Périquet et al., 2018).

1.2. Agency involvement in WVC data collection

Alongside volunteer-contributed data, government agency recording of infrastructure-incidents exist that can facilitate WVC research. An example of this, is police-collision-databases, which usually only include incident data that meet a minimum threshold of reporting (for example, occurrences involving property damage or a human injury or fatality). However, these data are subject to reporter bias, and may not be consistently or publicly reported, often lack information needed by environmental agencies, and may not contain information regarding species involved. In saying this, government data can be used, if reliable species and locational data of the WVC are provided to identify crash hotspots (Shilling and Waetjen, 2015; Bíl et al., 2017). There are, however, likely to be many false negatives in these datasets, as a WVC is only recorded if the attending police have physical evidence. In certain instances, transportation maintenance companies may be contractually required to report WVCs (for example, Alberta, British Columbia, and certain toll company concessionaires in South Africa), and provide excellent coverage of highways as they are often required to drive routes daily to monitor road conditions (Williams et al., 2019). In the UK, local authorities respond to reports of roadkill as a ‘hazard’ by members of the public, so producing detailed records of location, and species in urban areas.

1.3. WVC data collection and conservation

Volunteer science has facilitated analysis of conservation and ecological processes at broad spatial and temporal scales (for example, Breeding Bird Surveys, Tulloch et al., 2013), far beyond the limit of traditional field studies (Wilson et al., 2013; Lawson et al., 2015) and is considered a new and rapidly-changing form of data collection and management technology (Ellwood et al., 2017). Volunteer-collected biodiversity information has been determined to be key to global biodiversity monitoring and for certain groups (e.g., birds) may be the primary source of data (Chandler et al., 2017). Wildlife killed on roads are a continuous source of these kinds of data and potential observers are constantly passing carcasses, which could provide an immense source of biodiversity data. The field of “road ecology” includes many published studies where volunteer, agency, and scientist-collected WVC data were used to assess ecological impacts at roadways. It is becoming increasingly common for these data to also be used in ecological studies, or in combined ecological and conservation studies (Schwartz et al., 2019). For example, Ha and Shilling (2017) used volunteer-reported WVC data to develop a deer distribution and deer-vehicle-conflict model for one-third of California. Other studies have utilized WVC records to track and predict the progression of mammal invasion at large extents (Berry et al., 2007; Caley et al., 2015). Volunteer involvement in WVC data collection is changing so fast that it is important to keep track of both what is possible and what new tools may be needed (see Shilling et al., 2015; Bíl et al., 2020).

Although large-extent WVC systems have been deployed throughout the world, there have been few evaluations of their features and limited recommendations for future developers (Shilling et al., 2015; Périquet et al., 2018). Shilling et al. (2015) provide a now-dated review of these systems, including modes for collecting data and dynamic uses of the data (for example, real-time event reporting). However, there is no systematic review of the global ecosystem of WVC-reporting systems. The aim of this article is to provide an overview of global current practices and approaches in WVC data collection and reporting in the context of both assessing impacts of roads on animals and people for conflict mitigation, and as a method for tracking wildlife population dynamics and distribution. Our review highlights how the current systems have converged on general principles for data collection, data management, and data analysis/visualization. We recognize that just studying WVC and relying on ad hoc data collection has biases and limitations. However, these can be quantified and data collection supplemented with regular surveys. We use this overview of global systems and practices as the basis for recommended specifications for standardized volunteer and agency data collection and reporting of WVC data. We present several of the largest and longest running WVC data collection programs in the world and from that position, offer perspectives on the current and future directions of opportunities for WVC data collection development. In turn, this provides clear and practical applications for improved use of WVC data in ecological and conservation research as well as guidelines for management of road networks and driver safety.

2. Methods

Based on our professional knowledge of the WVC-research community and literature review, we identified WVC observation systems globally, operating at different extents. We contacted the developers and managers of each system to collect vital information about each system. For each system, we collated: 1) the system goals and objectives, 2) data collection methods and technologies, 3) the data management and visualization software and rule-basis, and 4) the decision-support considerations and tools. We addressed the technology and human interactions required to maintain data collection through these systems as well as the sharing of data within and among databases. We examined the current web-displays of data that assist interested and affected parties to visualize current and recent WVC findings. We addressed the various methods that data analysis/visualization can be, or is used in, transportation/ecological decision-making, and what possible barriers exist to prevent success. We compared and contrasted the features and attributes of all systems in order to derive consensus characteristics of successful systems, where success was determined by longevity, number of contributed observations, number of users, and use of the data in research and practice. We used this information to provide a framework of specifications for successful WVC observation and reporting, that can be adapted and applied for each situation, organizational need, and availability of reporting platforms.

3. Findings and recommendations for transportation and conservation

Our search resulted in the identification of 15 different projects collecting data on WVC on various geographical scales – from regional to national extents. Ten national scale projects were identified in: South Africa, Taiwan, Sweden, the Czech Republic, the United Kingdom, Ireland, Romania, Israel, Cyprus, and Austria. Additionally, three state (California, two systems, and Maine in the United States), one provincial (Alberta, Canada) and one regional scale program (Flanders, Belgium) were also identified. Participants in these programs varied considerably (for example, volunteer-scientists, hunters, road agency personnel) to specifically volunteer-reporting based or solely agency-based reporting (Table 1). We are aware that other systems exist around the global, but we focused on mature systems in our overview and summary description.

WVC threatens wildlife populations and species, with the degree of threat to wildlife dependent on rate of impact relative to wildlife population size/growth. To measure degree of threat and respond appropriately, it is essential to collect, manage and analyze observation data using standard protocols and systems that are transparently specified and reproducible. The following sections summarize characteristics we think have made current, mature systems successful and describe recommended approaches and specifications for the combined social-technical systems essential for WVC-reporting.

3.1. WVC observation system goals

All global WVC data collection systems operate under some aspect of this broadly-stated goal: "*The system is designed to monitor the occurrences of roadkill in order to improve safety for drivers, reduce impacts to wildlife populations, and contribute to the understanding and preservation of regional biodiversity*." (Shilling et al., 2015).

Despite this commonly-expressed type of goal, the connections between the data collection/analysis steps and decision-making processes to reduce harm simultaneously to humans and wildlife vary greatly among the global systems. Three of the systems (AWW, SZ, WI) were created and are supported by provincial or federal governments. This theoretically positions the data collection and analysis closer to the loci of decisions to primarily mitigate harm to human life and has resulted in transportation projects to reduce WVC in Alberta and California. The remaining systems were created by a University or an NGO, underpinning state/provincial or federal government needs (Table 1). These differing systems often result in diverging priorities; for example, the primary concern of a transportation agency is to preserve human life, while a conservationist's focus is wildlife.

Recommendations: We advise setting goals because it is important for both identifying and recruiting participants in data collection, as well as helping to define the methods that will be used to address system goals. Two examples are outlined below:

1. The best approach for addressing the goal of improving driver safety (Table 1) is to record "incidents resulting from collisions with animals that are large enough to change the trajectory of the vehicle (that is, a crash)", or "accidents resulting from drivers trying to avoid collisions with any-sized animals" (Shilling et al., 2015; Vanlaar et al., 2019).
2. The goal of conserving biodiversity requires approaches different from those related to driver safety to provide useful ecological data. Data collection should include recording sampling effort, age and sex of carcasses, photographs of carcasses (especially for uncommon species), and rate of carcass loss from the roadway (Williams et al., 2019). These metadata could aid in estimating impacts to populations of particular species.

3.2. Data collection infrastructure

The dawn of modern computing technology provides many tools for data reporting, be it through a cellphone, smartphone, tablet, or personal computer (Chandler et al., 2017). With over five billion smartphone users globally, they offer many people interested in volunteering the opportunity to monitor and investigate environmental phenomena; smartphones can both democratize and disperse monitoring effort to cover many bioregions, conditions, and environmental processes (Olson et al., 2014; Vercayie and Herremans, 2015; Chandler et al., 2017).

There are three types of applications useable on smartphones that can be employed to record roadkill: a) social media platforms (such as Facebook, Twitter and Instagram), and Short Message Service (SMS) or other text-based reports (such as WhatsApp or Facebook Messenger), which may or may not have associated images; b) "pure" smartphone apps (that are independent of a browser) that often use data-forms to record observations and associated images; and c) web-applications (that is, browser-dependent) that have been designed to be useable on a smartphone screen (also see Shilling et al., 2015).

Data contributed through smartphone apps, typically requires user/organization registration log in details before any data can be submitted. In most cases, the date and location are automatically filled in using the phone's GPS, but they can be modified, for example, by manu-

Table 1

An overview of examples from around the world of national and regional WVC observation reporting systems, including system locations and characteristics. * Goal 1 – Biodiversity protection and information gathering; Goal 2 – Driver safety protection, Goal 3 – Information system for hunters (focus on game animals), Goal 4 – Public engagement through the inclusion of citizens in science, Goal 5- Reporting to stakeholders to alter policy. ** Platform types: S – Smartphone Accessible, W – Website, G – Government (e.g., police, maintenance staff) reports, T – Text/SMS, SM – Social Media, E – Email, DB – Database Requests/Uploads. *** Government staff includes roadway maintenance staff and police; Public includes volunteers and any member of public; Nature Organizations includes private non-governmental organizations. **** Species list "complete" refers to lists that include all species likely to occur in the reporting area, while "restricted" refers to lists that are subsets of a complete list and have been constrained by system administrators,.

	Title, organization, country URL (acronym)	Year launched	Area	Goal Type *	Infrastructure	Platforms for reporting **	Who reports? ***	Species List ****
1	Alberta Wildlife Watch, Government of Alberta, Canada https://albertawildlifewatch.ca/ (AWW)	2016	Alberta, Canada	2	Roads	S	Government staff and contractors	Restricted
2	Animal-Vehicle Collisions, CDV, Czech Republic, http://Srazenazver.cz (SZ)	2014	Czech Rep.	1, 2, 3	Roads Railways	S, W, G	Government staff, public, nature organizations	Complete
3	California Roadkill Observation System Road Ecology Center, United States :https://wildlifecrossing.net/california (CROS)	2009	California, USA	1, 2,5	Roads	S, W, G, DB	Government staff, public, nature organizations	Complete
4	California Highway Incident Processing System Road Ecology Center, United States https://roadecology.ucdavis.edu/chips (CHIPs)	2015	California, USA	1, 2, 5	Roads	G	Government staff	Complete
5	Cyprus Roadkill Observation System http://www.cyroadkills.org	2017	Cyprus	1, 2	Roads	S, W	Government staff, public, nature organizations	Restricted
6	Dieren onder de wielen Natuurpunt, Belgium German: http://www.dierenonderdewielen.be International: http://www.observation.org/vs/start (subsite of general nature observation portal world.observation.org) (DOW)	2008	Flanders (northern part of Belgium), but works elsewhere in the world too	1, 2	Roads	S, W.	Government staff, public, nature organizations	Complete
7	Maine Audubon Wildlife Road Watch Road Ecology Center and Maine Audubon, United States http://wildlifecrossing.net/maine (MAWRW)	2010	Maine, USA	1, 2, 4, 5	Roads	W	Government staff, public, nature organizations	Complete
8	Project Roadkill Institute of Zoology, University of Natural Resources and Life Sciences, Vienna, Austria http://roadkill.at/en/ (PR)	2014	Austria, but data collection is possible globally	1, 2, 4, 5	Roads	S, W	public, nature organizations	Complete
9	Project Splatter Cardiff University, United Kingdom https://projectsplatter.co.uk/ (PS)	2013	UK (England, Scotland, Wales, and Northern Ireland)	1, 2, 4, 5	Roads	S, W, G, SM, E, DB	Government staff, public, nature organizations	Complete
10	Road.kill https://road-kill-registration.green-web.eu/?lang=en	2019	Romania	1, 2	Roads Railways	S, W	Government staff, public, nature organizations	Complete
11	Road Watch Endangered Wildlife Trust, South Africa https://play.google.com/store/apps/details?id = com.ewt.ewtroadwatch&hl = en (RW)	2013	South Africa	1, 2, 4, 5	Roads Railways Power lines	S, W, G, E, SM, T, DB	Government staff, public, nature organizations	Complete
12	Society for Protection of Nature in Israel (SPNI) System used: the WAZE app	2016	Israel	1, 2	Roads	S	Public	Restricted
13	Taiwan Roadkill Observation Network https://roadkill.tw/en	2012	Taiwan	1, 2, 3	Roads	S	Government staff, public, nature organizations	Complete
14	Viltolycka, Nationella Viltolycksrådet, Sweden, http://www.viltolycka.se	2007	Sweden	2	Roads	G	Government staff	Restricted
15	Wildlife Incident Ireland http://wildlife-incidents.com/ (WI)	2015	Ireland	1, 2, 4	Roads	S	Government staff, public, nature organizations	

ally dropping a pin on a map. Systems vary between required versus optional metadata (for example, photographs) when a user submits an observation. While some volunteer-science projects have a standardized methodology for data collection, most systems allow for the submission of anonymous, opportunistic or ad hoc observations, even though these are often perceived to be of lower quality (Bird et al., 2014).

When smartphones are used to record images, they can store valuable information in the Exif (Exchangable Image File Format) data associated with the image. When the GPS/location function of the phone is enabled, the Exif data includes the Latitude/Longitude coordinates of the image, which already contains the date/time of the image. The importance of this is that the metadata-enriched image file can be transferred by the smartphone user to a server-side application that builds a database record based upon the Exif data. The CROS system uses the Exif data from images uploaded from smartphones to create the location and date/time parts of an observation record. Using images as the data source also provides a mechanism to manually verify species; this allows records to be assessed for accuracy and completeness.

While smartphone app systems and browser-dependent applications are the more commonly used platforms for data reporting, they do differ in key respects. For example, smartphone apps can sometimes access more on-phone functions than web-applications and web-apps may provide more tools to the user than smartphone apps.

Smartphone apps are often looked to as the solution for low-cost, large-scale biodiversity data collection by volunteers; however, this may involve a “cost-paradox” where the “free data” is accompanied by the many costs of creating and updating app-compatibility (Andrachuk et al., 2019). Often the cost of developing and maintaining a web or smartphone app can vary considerably and development and maintenance of data-collection and management technology can be the largest portion of the overall cost. However, this initial cost must be balanced against the overall benefits such as recruiting and working with volunteers and data analysis/visualization (e.g. Heigl et al., 2017). For example, the Austrian ‘Project Roadkill’ uses software (website and apps for Android and iOS) provided by the company ‘SPOTTERON’ which specializes in citizen science projects, whereas the South African app (Road Watch) was developed by a volunteer (at no cost) and the website is managed ‘in-house’ at the EWT. Despite possible financial overheads, development costs are decreasing as more open-source and free tools are made available (e.g. Epicollect, Waze), with many of these apps providing options to report live or dead animals on the road.

Recommendations: We suggest paying careful attention to what tools people need or want to easily collect data as this may be an important barrier, or opening for public and government staff participation. We also suggest aligning data models and formats as much as possible among national and global systems to facilitate best practices and sharing of data collection, management, and analysis tools. Finally, although we don't recommend forming a single global WVC observatory, there may be advantages to this approach in terms of funding, maintenance and coordination of data collection protocols. WVC data are likely to come from three primary sources and accommodations should be made to use and collect all three (Fig. 2A). These are outlined below:

1. Developers of WVC reporting projects should consider other wildlife recording portals available in their region as good starting points to expand upon an existing naturalist user-base, where WVC observations may be incidental to the project. This may require a two-way data transfer between these other portals and the developer's system;
2. A second primary source will be novel data collection by volunteers. In this case, providing several reporting platforms through varying the tools for data submission allows for maximum participation from data contributors; and,
3. The third source will be government reporting of WVC-crashes or roadkill, either from state police or roadway maintenance staff. In this case, government entities may or may not have or want to use their own, or third party WVC reporting tools. However, this may be one of the largest continuing data sources for large animal events and will be important in both telling the WVC story and informing actions on infrastructure to mitigate WVC.

3.3. Data management systems

Most contemporary wildlife/roadkill observation and reporting systems operate through a web-system. Automated querying and visualization tools in web-systems require certain, exacting data/metadata formatting. These typical requirements have resulted in common approaches to data management. For example, in CROS, CHIPs and SZ, there are technology and application stacks on the data-managing server composed of an operating system, a content management system, a relational database, map tools for data entry and visualization, and associated tools in common language environments (for example, Java) to run and operate various routines based on PostgreSQL/postGIS scripts (e.g., Fig. 1; Bíl et al., 2017; Waetjen and Shilling, 2017).

Data from different sources are integrated in some WVC data management systems. For example, in the Czech Republic (SZ), police reports of WVC are entered directly into a system that contains both roadkill and crash data. A similar process is used in Alberta (AWW), except that the traffic incident reports (involving a WVC) are analyzed separately from the mobile application receiving roadkill data. Once data have been uploaded to the server, they typically go through a validation process. This process is entirely manual in some systems (for example, RW and PR), others use automatic filters to detect common errors and notify a system administrator and some systems use both (DOW).

Data analysis and visualization is conducted on large datasets with presumed consistency in data format and accuracy. Many, if not all the features and requirements of a dataset that derive from typical WVC-reporting systems also lend themselves to automated processes. Setting up data management through a web-system and component technology stack can be time-consuming; however, employing a web-system is essential for web and smartphone app-based reporting. It can also provide many advantages for data organization and relationships, since the initial requirements for structure and format may be greater than for spreadsheet organization. Ultimately, these time investments pay off over time, and we therefore recommend that new systems adopt web-systems to collect and manage observation data (Fig. 2).

There are existing platforms that can be emulated (see Table 1, for example) and published database diagrams that can be copied (for example, Waetjen and Shilling, 2017). We suggest using non-commercial platforms to collect and organize data since commercial software may require ongoing costs that may be periodically difficult to meet, and data may be more difficult to share among platforms and partners. In some cases, a commercial approach may be affordable and more appropriate for some organizations since it is less time-consuming to design a thorough database at the onset rather than having to employ modifications at a later stage. It may also be worth consulting with stakeholders, volunteers, and data-users before finalizing a web-database structure and workflow, or undertaking a pilot project to assess the preferred platforms of reporting.

Recommendations: Through consultation with a web-designer, we recommend that the design of a new WVC reporting system use the data format approaches of existing systems, which are typically based on five principles; the “where”, “what”, “when”, “how” and “who” principles. Additional features may include providing real-time access to

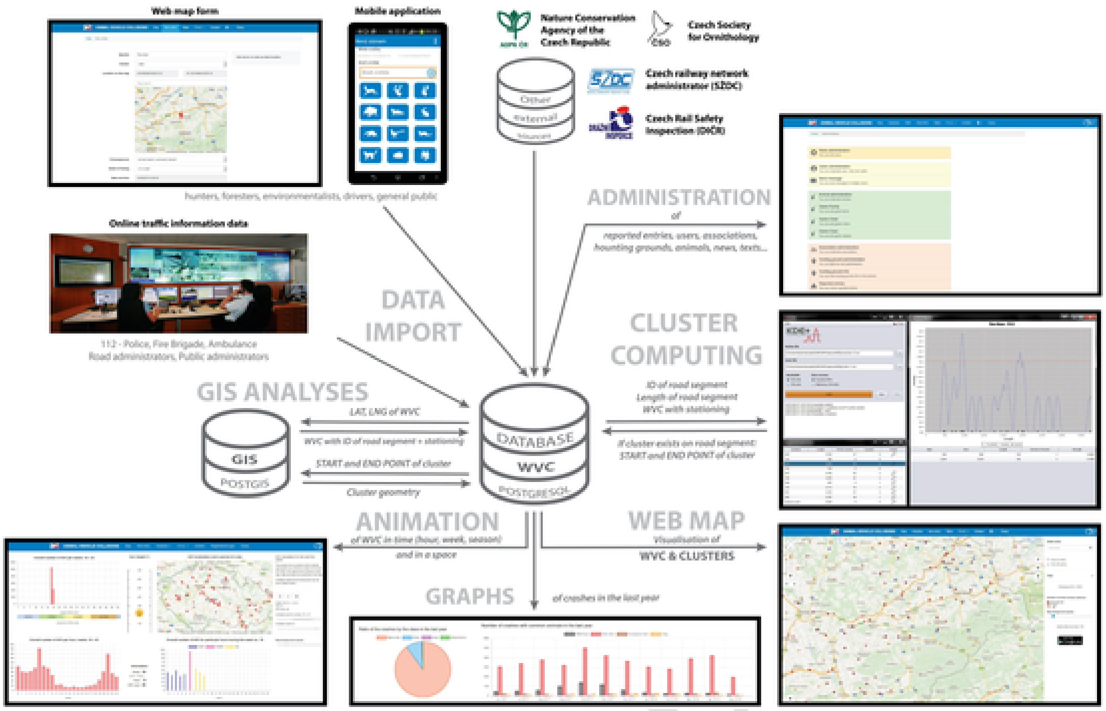

Fig. 1. Technology stack for WVC data management, with automated processes, server applications, and map-visualization (SZ, Bíl et al., 2017).

specific data, such as individual species, WVC densities, or clusters or the entire database. Exporting data as comma-separated values (.csv) files allows optimal data-sharing, including within the reporting system.

To build confidence in systems that involve WVC-reporting by volunteers or non-expert agency staff, the databases should support validation of data entry completeness and accuracy (for example, species identification and/or locational accuracy). One example method to secure data quality is Project Roadkill (AT), which implement a stepwise selection process to classify all submitted data to three quality levels: (1) consistent datasets with correct species identification (verified either by an expert or accompanied by a photograph); (2) datasets with consistent data, but no validation of the animal species; and, (3) datasets with inconsistent data and no validation of the animal species; these data are archived.

Based on our knowledge and shared experience, we recommend the following considerations as part of the quality assurance process for a WVC data collection system:

1. Consider sending automated updates to reporters when submitting their report (for example, migrating species that are not present at the time of data entry);
2. Validate data by experts after the observation is submitted by the user, preferably before the data is exported or used for analysis;
3. Explore automated species validation systems based on image recognition;
4. Implement a quality ranking system for datasets for verification of the submission. This could be via a photograph or the reliability and expertise of the reporter; and,
5. Explore opportunities for automation, particularly with respect to identifying duplicate observations of the same animal.

3.4. Data visualization systems

This final step in the WVC reporting system completes the loop between the initial conflict event and informing parties that can reduce the impacts (Fig. 2B). One tremendous advantage of WVC data uploaded to a web system is the almost instantaneous generation of WVC maps, through which users can query and display specific species or taxa, as well as time periods and/or geographic regions. The most commonly used web and base maps are Google Maps API and Open Street Map with road and satellite photo options, but others include Leaflet, Nette framework, HTML, and JQuery. Importantly, WVC data display can support social and management decisions. These include periodically updated maps, charts, statistics and lists of WVC incidents and hotspots calculations. Analyses that provide incident density and spatial clustering outputs can inform transportation and conservation planning, while real-time clustering data could inform driver decisions in connected automated vehicles.

Current hotspot analysis tools in use include KDE+ software (Bíl et al., 2013; Bíl et al., 2016), Google maps (RW), Getis-Ord (CROS, Shilling and Waetjen, 2015), and incident density (Shilling and Waetjen, 2015; Bíl et al., 2017). With a few exceptions (SZ, AWW), hotspot analyses are generated manually. In California, maps displaying hotspot analyses are overlaid with "real-time" records of deer-vehicle collisions, which are updated every 15 min (https://roadecology.ucdavis.edu/hotspots/map). The Swedish National Wildlife Accident Council (Nationella Viltolycksrådet) developed a smartphone app (called Viltolycka, https://play.google.com/store/apps/details?id=se.viltolycka.android&hl=nl) based on their extensive WVC database which warns drivers when they approach a spot where WVC have happened in the past so they can adapt their speed and vigilance appropriately.

Recommendations: One of the most important decisions regarding data analysis and visualization will be to identify the intended audience, and therefore, how the analysis and graphical outputs are portrayed. The audience may range from the general public to technically knowledgeable managers, varying according to an individual project's remit (Table 1). It is also critical to provide feedback on data submitted, and not just through obligatory reports to the road agencies. To meet certain objectives, social media should be considered as an important and powerful tool, not only as a primary awareness-raising plat-

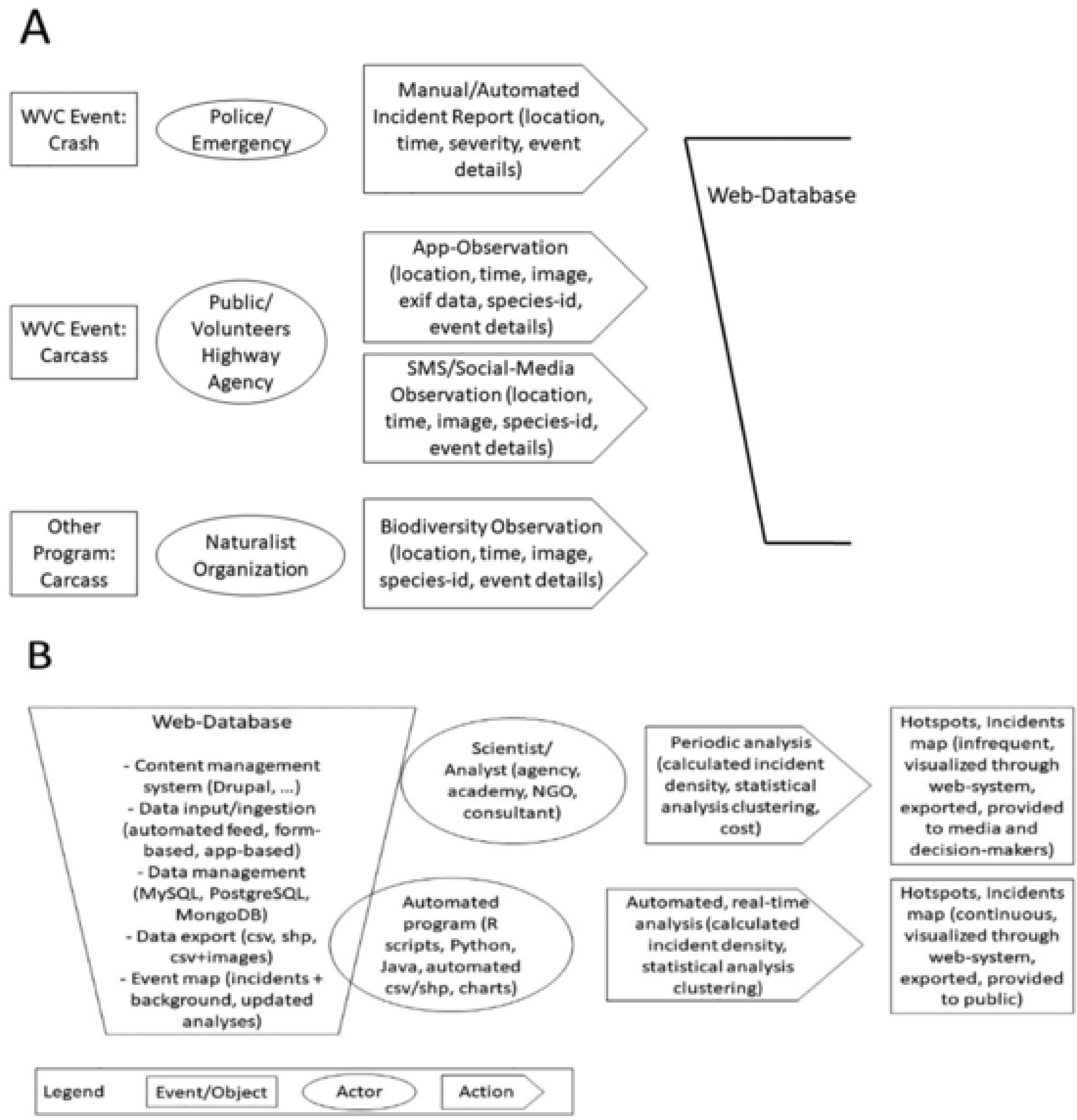

Fig. 2. Work-flow for idealized WVC reporting system. A) Data inputting types and processes; B) Data management, analysis, and visualization.

form of WVC, but in reinforcing and expanding relationships with data contributors, whether they are volunteers or government agency staff. Where possible, WVC reporting systems should include dynamic maps that represent the outputs of the data analyses, such as roadkill hotspot maps, which usually convey critical information for decision-making. However, other forms of analysis are equally important such as estimating total WVC in an area from available data, estimating the economic impact of WVC, or identifying areas of aversion where there are few WVC, and comparing WVC rates with other information about wildlife movement (Garriga et al., 2017; Nelli et al., 2018).

3.5. *Who participates in data collection and how do they participate?*

Involving the public, members of conservation organizations, and employees of transportation/agencies in wildlife data collection is already happening at large extents and globally, dozens of web-based systems for reporting roadkill exist (https://globalroadkill.net; Table 1). In most projects, participants report data about roadkill during their daily routine. If the participants see a road-killed animal, this is reported using the respective system. This type of reporting is therefore based on random findings, or so called opportunistic or ad hoc observations, if the participants do not drive or walk the route at regular intervals. There are also national systems in many countries for reporting wildlife in general, which often includes being able to report roadkill (for example, iSpot, Africa:Wild, MammalMap, observation.org, waarnemingen.be, National Biodiversity Network Atlas). These systems vary greatly in purpose and taxonomic focus and they may or may not provide data in a way that can be exchanged with WVC-reporting systems.

Most systems allow carcass observation entries to be submitted by any individual, or person affiliated with an organization (Table 1). This could include observations from anonymous, or registered users. Several systems only allow data submission by state police/government (AWW, VO), or retrieve data from police/emergency-response systems (CHIPs, SZ). The CROS System has a ~ 95% species identification accuracy, as determined from uploaded images (Waetjen and Shilling, 2017; Tiedeman et al., 2019). However, there has been some debate regarding the ability to submit a roadkill report with a photograph. It may not be safe to exit the vehicle or even legal. These restrictions can have a significant impact on the absolute or relative number of WVC being reported. In both the Czech Republic (SZ) and Maine (MAWRW) projects, volunteers are trained in data collection and it is mandatory to wear safety equipment when undertaking surveys on roads.

Certain systems capture observations from very diverse groups and have correspondingly diverse data collection methods. For example, South Africa's Endangered Wildlife Trust (EWT) collects observations using the smartphone app, 'RoadWatch' (https://play.google.com/store/apps/details?id=com.ewt.ewtroadwatch&hl=en), social media channels, web-forms, and instant messaging, which all allow roadkill data to be submitted from both ad hoc observations and regular transects. In addition, road patrol teams from three of the country's national toll road routes, have been trained in roadkill data collection, and gather data daily. Partnering with road agencies for data collection offers considerable opportunities to identify factors related to roadkill distribution and reduce the threats posed by roads to wildlife. The Czech Republic's SZ focuses on a specific group of volunteers who are hunters and hunting-ground administrators and much of the data on roadkill come from this group of users. The Czech Republic is divided into thousands of hunting districts and each hunting group is required to annually report to the Ministry of Agriculture, an overview of animals killed.

In addition to the technical aspects of developing WVC data collection, management and sharing systems, it is critical to respect the role that data contributors play. Direct, face-to-face interaction between project leaders and volunteers leads to better outcomes for the overall data-collection endeavor (Cappa et al., 2016). For example, using events like "Roadkill Awareness Days" (RW, South Africa) provides an opportunity to engage with members of the public and encourage them to report roadkill sightings. This also generates further opportunities to undertake research questionnaire surveys to gauge public perception of roadkill and how aware they are of it as a threat to biodiversity. Resnick et al. (2015) provide a framework for the ethical treatment of volunteers, including consideration of the data quality, data sharing/ownership, any conflict of interest, and exploitation. The Citizen Science Network Austria developed a quality criteria catalogue for citizen science projects, covering scientific, collaboration, communication, open science, and ethical aspects (Heig et al., 2018). Among the WVC-reporting systems reviewed here, the majority have at least indirect, electronic communication with WVC observers, with an exceptional few involving volunteers in special WVC studies (for example, CROS, carcass loss rate study), training (e.g., MAWRW, RW road patrol teams), and discussions of image-data ownership and sharing.

Recommendations: We advocate that organizations consider the following when developing relationships with prospective data collectors/partners:

1. Who are the different target groups that will participate in data collection and what is their motivation for contributing to your project? Based on our experience, we recognize four main types of data collector from our WVC observation systems:

I. System organizers;
II. Opportunistic volunteer or agency data collectors;
III. Regular volunteer or agency staff surveyors; and,
IV. Organizational data users and analysts.

2. Different data collectors may have varying agendas when involving themselves with the project; however, their goals should be respected as they are the primary data collectors and are at least co-owners of the data. Consider what the advantages or disadvantages of working with each of those groups are;
3. Consider what the impact of the chosen target group has on the amount and quality of the data you receive. Involvement of volunteers may provide dual and complicated roles; as observers they will expect feedback for their efforts, and you, as the project leader will need to find time to engage with them and provide relevant feedback. Therefore, consider too, how will you provide feedback and regularly communicate to participants?
4. What is your plan for keeping volunteers engaged and motivated? Recruitment and retention of volunteers and agency staff collecting carcasses is currently critical to the survival of WVC observatories. Supporting their involvement should consist of effective communication with them as a group, one-on-one interaction and use of mass-media to both announce progress and to recruit new participants; and,
5. How will you build a volunteer or other user-base (if you are starting from scratch)? Are there options that can give you a head start (for example, by partnering with another active naturalist community or in the case of a volunteer-based project, listing on national or international citizen science platforms (e.g. https://scistarter.org/, https://eu-citizen.science/ or https://www.citizen-science.at/en/). Consideration should be given to following guidelines for working with volunteer-scientists, for example from the European Citizen Science Association.

3.6. Informing transportation and conservation decisions

When launching a reporting system that is not necessarily mandated at a governing level, developers may face challenges to obtain 'buy-in' from the various forces required to endorse and utilize the information. This may require building a business case for gathering WVC data and the cost benefits associated with this approach. Within the US, the Czech Republic, Belgium, South Africa, and the UK, the CROS, SZ, RW, DOW, and PS systems have no official position in state decision-making, but regularly receive data-requests from state agency staff to provide analyses and to design projects. Similarly, in Austria, Project Roadkill shares data with local NGOs which base decisions on locations of temporary amphibian fences, for example. The nature of the data and analyses mean that less interpretation is needed by responsible government entities to use the data in decisions.

Recommendations: To obtain 'buy-in' at a government level may require one or more of several methods proposed below:

1. Demonstrate impacts to particular species of conservation, legal or public concern at local or regional levels in order to inform species-protection projects.
2. WVC reports provide an indication of conflict between vehicles and wildlife that could be severe enough to warrant action. The nature and type of mitigation action and whether or not anything is done depends, in part, on the rate and severity of WVC. At the same time, the rate and extent of complete WVC reporting may have a strong influence on the perceived need for action. We recommend that those designing WVC reporting systems consider: on what basis must a decision about mitigation be made?
3. One of the most important pieces of information needed to use WVC data in ecological studies is a measure of observer/sampling effort. In several cases (e.g., CROS, MAWRW), the user can enter the frequency that they drive a particular road segment. Assuming this information is accurate, later analysis can include this as at least a minimum estimate of sampling effort. Because analyses of carcass data often require knowledge of observer efficiency and sampling frequency (e.g., Korner-Nievergelt et al., 2015), it is important to consider how to collect this type of information from volunteer-observers, who may not think of their participation in these terms.
4. Translate WVC data for decision-making as a business model, by calculating the equivalent financial cost of WVC per unit time and/or roadway segment, or jurisdiction (see, CROS, CHIPs, SZ). This assumes that information is available about the type and severity of

crash and animal species involved. This cost/year-km can help justify projects with benefit-cost analyses; and,

5. A critical part of the decision loop about WVC is that there is usually no set threshold of response from any government agency in the world. This means that the decision to act is almost always based entirely upon political and social considerations, rather than a calculated response based upon exceeding thresholds, or quantification of a problem.
6. If a rational system is in place that supports mitigation measures to reduce roadkill and improve driver safety, it may be sufficient to identify hotspots (e.g., of collisions or aversion) and calculate the total ecological impacts and financial damages; and,
7. If there is no systematic inclusion of WVC assessment and mitigation as part of business practices (which is the case in the US), then most actions will be discretionary and in response to the concerns of a local champion (or the power of social media), or fear of liability. WVC reporting may still have a role in these cases by providing a combination of WVC reporters, structured data collection process, science-based analysis, and graphical representation of WVC problems.

4. Conclusion: potential steps toward a global volunteer WVC reporting system

In this review we have identified common principles that can help existing and new WVC observatory developers and help lay the foundation for a global WVC observatory, composed of national and regional nodes. Based on these principles, we developed a series of recommendations that can be used to design a WVC reporting system at a regional or national scale, described in Section 3 above. We did not attempt to anticipate all the nuances that a reporting system will face during development, but we believe that the practices recommended will facilitate deployment of a successful system. We also recognize that WVC reporting is only a fragment of the total picture of understanding this type of conflict.

There are six important and complementary revolutions and concepts that contribute to a promising future for volunteer-based WVC observatory systems:

1. More and more people are participating in volunteer observations of all kinds, including of the environment (Ellwood et al., 2017). As news media and other coverage of this phenomenon has increased, so have the rate and breadth of volunteer involvement. Growth will depend on outreach and reinforcement of the connection between the volunteer and the observatory project as well as maintaining volunteer recruitment and retention after the project ends, which should also be a consideration;
2. Data reporting and management of large and diverse datasets (for example, Chandler et al., 2017) has been enabled through the constant use of handheld devices, meaning that every potential WVC observer already has an instrument at hand. WVC reports are increasingly formatted very similarly across wide geographies and ranges of observation types. Standardization of records and association of images means that platforms can more easily be shared, reducing the up-front learning and financial costs for new projects. In addition, employment of common data collection and management tools could facilitate the development of a global observatory for WVC, while potentially reducing costs for each individual program;
3. There are over five billion mobile users in the world, with global internet penetration standing at 57% (Iqbal, 2019). As of the first quarter of 2019, app users could choose to download between 2.6 million Android, and 2.2 million iOS apps, with social media apps being the most-popular apps in the world (Iqbal, 2019). Consequently, developing your own app must make an instant impression, due to the vast choice of wildlife apps available (some of which provide opportunities to record wildlife data, such as sightings in national parks, or assistance with the identification of trees or bird calls). In addition, organizations in charge of reporting systems almost without exception (including the authors) want their branding on the platform (Andrachuk et al., 2019).
4. Not all potentialvolunteers are likely to prefer the same method of collecting data. Thus, some individuals will be engaged by an interactive website (Swanson et al., 2015), while others prefer a smartphone app, and another group may prefer email communication. At the same time, reducing differences among the data/metadata formats and standards will reduce the costs associated with developing and managing tools as existing tools for data collection, management, analysis, and visualization can be more easily shared;
5. The use of WVC data in transportation and conservation advocacy, planning, and decisions means that image-based records are more easily verified, supporting perceptions of data accuracy. Geospatial data management and visualization can make data more easily shared and brought into decision-support. Volunteer networks can provide extensive, long-term, and accurate data that may not otherwise be available to many agencies. Finally, WVC data are being used in ecological studies to study invasion, population and species well-being, and disease (Creley et al., 2019; Schwartz et al., 2019).
6. From a wildlife perspective, it is important to remember several things about WVC:

a) Absence of WVC does not indicate the absence of an impact to a species;
b) WVC represents a continuing and usually unmitigated impact of a facility;
c) Numbers and species of killed animals must be compared to population structure and size to understand the full impact of the mortality on the species (adapted from Shilling, 2008; Williams et al., 2019).
d) From the larger frame of efficient and sustainable transportation, WVC represents both a tangible harm to wildlife and the public, as well as a soluble problem, where contributing to sustainability begins with first reporting and understanding WVC.

WVC data collection currently provides one of the largest, continuous source of observations of diverse wildlife in the world. These data are useful information for preventing the WVC event itself and conserving wildlife. They are also biological monitoring data that can be used to help develop species distribution models, to monitor sizes of wildlife populations, to track animal invasions, and to herald species recovery or re-discovery. As WVC data collection spreads and is enriched by the scientific approaches we recommend, a truly global observatory system will emerge, benefiting biodiversity monitoring and protection.

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