Biological Conservation 256 (2021) 109076

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

COVID-19 related travel restrictions prevented numerous wildlife deaths on roads: A comparative analysis of results from 11 countries

Michal Bíl[a,*], Richard Andrášik[a], Vojtěch Cícha[a], Amir Arnon[b,c], Maris Kruuse[d], Jochen Langbein[e], András Náhlik[f], Milla Niemi[g], Boštjan Pokorny[h,i], Victor J. Colino-Rabanal[j], Christer M. Rolandsen[k], Andreas Seiler[l]

[a] CDV Transport Research Centre, Lisenska 33a, Brno 636 00, Czechia
[b] Department of Evolutionary and Environmental Biology and the Institute of Evolution, University of Haifa, Haifa 3498838, Israel
[c] Ramat Hanadiv Nature Park, Zikhron Yaakov 3095202, Israel
[d] Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
[e] Langbein Wildlife Associates, Greenleas, Chapel Cleeve, Minehead TA24 6HY, United Kingdom
[f] Institute of Wildlife Management and Vertebrate Zoology, University of Sopron, Bajcsy-Zsilinszky Sopron H-9400, Hungary
[g] Metsähallitus Wildlife Service Finland, Pohjoispuisto 7, FI-28100 Pori, Finland
[h] Environmental Protection College, Trg mladosti 7, 3320 Velenje, Slovenia
[i] Slovenian Forestry Institute, Večna pot 2, 1000 Ljubljana, Slovenia
[j] Section of Zoology, Department of Animal Biology, Parasitology, Ecology, Soil Science and Agrochemistry, University of Salamanca, Campus Miguel de Unamuno, 37071 Salamanca, Spain
[k] Norwegian Institute for Nature Research (NINA), P.O. Box 5685, Torgarden, NO-7485, Trondheim, Norway
[l] Swedish University of Agricultural Sciences, SLU; Grimsö Wildlife Research Station, 73091 Riddarhyttan, Sweden

ARTICLE INFO

Keywords:
Wildlife-vehicle collisions
Wildlife crash reporting systems
Traffic flow
Ungulates
Mesocarnivores
COVID-19 lockdown

ABSTRACT

Millions of wild animals are killed annually on roads worldwide. During spring 2020, the volume of road traffic was reduced globally as a consequence of the COVID-19 pandemic. We gathered data on wildlife-vehicle collisions (WVC) from Czechia, Estonia, Finland, Hungary, Israel, Norway, Slovenia, Spain, Sweden, and for Scotland and England within the United Kingdom. In all studied countries WVC statistics tend to be dominated by large mammals (various deer species and wild boar), while information on smaller mammals as well as birds are less well recorded. The expected number of WVC for 2020 was predicted on the basis of 2015–2019 WVC time series representing expected WVC numbers under normal traffic conditions. Then, the forecasted and reported WVC data were compared.

The results indicate varying levels of WVC decrease between countries during the COVID-19 related traffic flow reduction (CRTR). While no significant change was determined in Sweden, where the state-wide response to COVID-19 was the least intensive, a decrease as marked as 37.4% was identified in Estonia. The greatest WVC decrease, more than 40%, was determined during the first weeks of CRTR for Estonia, Spain, Israel, and Czechia.

Measures taken during spring 2020 allowed the survival of large numbers of wild animals which would have been killed under normal traffic conditions. The significant effects of even just a few weeks of reduced traffic, help to highlight the negative impacts of roads on wildlife mortality and the need to boost global efforts of wildlife conservation, including systematic gathering of roadkill data.

1. Introduction

It has been estimated that some 194 million birds and 29 million mammals are killed annually on European roads (Grilo et al., 2020). For ungulates alone, over half a million wildlife-vehicle collisions (WVC) are recorded annually in nineteen European countries (Linnell et al., 2020), with estimates for Europe as a whole exceeding 1 million per year (Langbein et al., 2011). Collisions with ungulates and other large mammals represent a major source of direct anthropogenic non-hunting wildlife mortality (Forman and Alexander, 1998) and socioeconomic

---

* Corresponding author.
E-mail address: michal.bil@cdv.cz (M. Bíl).

https://doi.org/10.1016/j.biocon.2021.109076
Received 18 September 2020; Received in revised form 2 March 2021; Accepted 9 March 2021

costs associated with human injury, death and vehicle damage (Bissonette et al., 2008; Niemi et al., 2017). It is also an animal-welfare issue as a high proportion of animals are injured but not killed in the collision itself, are not always found and put to death, and therefore live on with injuries or die from the injuries sometime after the accident (Putman et al., 2011).

In most cases, it is large animals such as ungulates which are reported, and for which databases exist with the number of accidents. Roe deer (*Capreolus capreolus*) is the most frequently reported road-killed large mammal in almost all European countries; Czechia (Bíl et al., 2017), Sweden (Jägerbrand et al., 2018; Seiler et al., 2019), Norway (Solberg et al., 2009), Hungary (Faragó and László, 2017), Slovenia (Pokorny, 2006; Oslis, 2020), Estonia (Kruuse et al., 2017) and Germany (Hothorn et al., 2012). Other species that dominate the accident statistics in parts of Europe are wild boar (*Sus scrofa*), red deer (*Cervus elaphus*), moose (*Alces alces*), and fallow deer (*Dama dama*) (Langbein et al., 2011; Linnell et al., 2020).

Concealed by the high total numbers of WVC, especially with ungulates, is the traffic mortality in species with small population densities. Considering only mammals, roadkill is a major factor which threatens almost all large carnivores (i.e., brown bear *(Ursus arctos)*, gray wolf *(Canis lupus)*, Eurasian lynx *(Lynx lynx),* Iberian lynx *(Lynx pardinus)*, and wolverine *(Gulo gulo)*, in the European human-dominated landscapes (Chapron et al., 2014; Garrote et al., 2018). Roads still present the main threat to Iberian lynx, one of the most endangered carnivores on the planet. Also, in case of European mink *(Mustela lutreola)*, listed as Critically Endangered (CR), roadkills presented the most common human-induced cause of mortality in 1990–2008 when 91% of individuals were killed by moving vehicles (Palazón et al., 2012). Data for other species groups such as lagomorphs, medium-sized carnivores (mesocarnivores) and avian wildlife are very scarce and often more unprecise and underreported (Bíl et al., 2017). Rough estimates, however, suggest that in total several million individuals of these species are killed in traffic each year (Grilo et al., 2020).

The frequency of WVC may be influenced by many factors that vary in space and time related to traffic and other road characteristics, weather, land use and structure, vegetation, animal activity patterns and population density (Langbein et al., 2011). Traffic volume is identified as one important factor (Pagany, 2020), but interannual changes in traffic volume are usually small, and over time there may be parallel increasing trends in both animal and car numbers that make it difficult to estimate the unique effect of varying traffic volume (Hothorn et al., 2015).

A unique situation occurred in the first half of 2020 when road traffic in many places decreased sharply as a result of both travel restrictions and reduced traffic demand in relation to the COVID-19 pandemic. This period of unusually reduced human mobility has been called ‘Anthropause’, and – although created under tragic circumstances – can provide a unique opportunity to gain insights into how (changes in) human activity affect wildlife (Bates et al., 2020; Corlett et al., 2020; Rutz et al., 2020).

This traffic decline provided a possibility to explore how this impacted WVC in different countries. In this study, we compared weekly reported number of WVC during the first 16 weeks following the COVID-19 lockdown in March 2020 with predicted values based on 2015–2019 time series. We investigated whether COVID-19-related traffic reduction (CRTR) resulted in significant WVC reductions in selected European countries and Israel. We also discuss to what extent the results seem to reflect the strictness of lockdown measures implemented in different countries.

2. Materials and methods

2.1. Study areas and data

We used WVC data from 11 countries: Czechia (CZE), Spain (ESP), Estonia (EST), Finland (FIN), United Kingdom (England and Scotland, ENG, SCO), Hungary (HUN), Israel (ISR), Norway (NOR), Slovenia (SVN) and Sweden (SWE). Altogether, we worked with 645,496 carcass data recorded between 1/2015 – 6/2020 (Table 1). For the purposes of this paper, we consider WVC either as all the reported collisions with wildlife (i.e., police records in some countries) or as WVC with a fatal outcome for the animal. As in some countries, e.g., in Slovenia, hunters are obliged and motivated to register and prove all roadkill of large mammals, such datasets may be even more comprehensive and reliable than official police records. The origin of the WVC data used in this study was (i) police crash data (CZE, ESP, HUN and SWE), (ii) carcass removal data (SCO) and (iii) data provided by hunters, rangers or wildlife managers (ENG, EST, FIN, ISR, NOR and SVN). Details about the WVC data sources are provided in Appendix A.

The CRTR period roughly delimits the spring peaks of WVC, which is quite evident in data from several countries (Fig. 1).

2.2. Description of CRTR

We set the beginning of CRTR as the 11th week of 2020 for all countries except ENG, SCO and SWE (12th week). During these weeks, European countries and Israel announced and implemented lockdown measures that also affected transportation and travel. The end of June was considered as the final week of CRTR in spring 2020, but in certain countries the official state of emergency only lasted one month (e.g., CZE). Road travel and especially private travel across national borders, however, then gradually increased and could therefore also affect the number of WVC after completion of the most intensive CRTR period (Fig. 2). Detail on traffic flow data for each country can be found in Appendix A.

2.3. Statistical analysis

We worked with weekly sums of WVC. First, we used available WVC data for 2015–2019 in order to build a seasonal ARIMA model (i.e., autoregressive integrated moving average model; Hyndman and Athanasopoulos, 2018). We then used this model to predict expected weekly sums of WVC in 2020. Consequently, actual recorded 2020 data (influenced by CRTR) were compared on a weekly basis with the forecasted data (Fig. 3).

Only data on WVC records were used directly in these analyses. Traffic intensity data were of varying quality, in some cases not representing entire countries, and therefore served merely as a demonstration of the traffic flow reduction.

Computations were performed in R Software with the library “forecast” (Hyndman et al., 2020) and routines “auto.arima” for an automatic selection of the model and “Arima” for further adjustments of the model. The initial family of fitted models stems from the default setting of routine “auto.arima”, it was ARIMA(2,1,2)(1,1,1)[52] using the notation from Hyndman and Athanasopoulos (2018). Akaike information criterion with correction for small sample sizes (AICc) was chosen for model selection. *Ljung-Box test* was applied to assess the quality (performance) of the resulting fitted models. It is a statistical test of whether any of a group of autocorrelations in a time series are different from zero, and is applied to the residuals of a fitted ARIMA model; the null hypothesis states that the residuals from the ARIMA model have no autocorrelation (for more details, see Appendix B).

In order to measure the reduction of WVC in a given period, a rate ratio (RR) was calculated. It compares the observed number of WVC (O) to the expected number of WVC (E) in a given period. RR was computed as the ratio of incidence rates. Since periods at risk are the same, RR reduces into a simple fraction: $RR = O/E$. We are interested in testing a null hypothesis “$RR = 1$” against an alternative “$RR \neq 1$”. The *rate ratio test* was applied (R Software, package “rateratio.test”). A rate ratio of 1.0 indicates equal rates, a rate ratio significantly greater than 1.0 indicates that a higher risk was observed than expected, and vice versa. Instead of

Table 1
The number of reported WVC in each country during the period (2015/2017–2020). The most frequently represented species in the respective WVC databases are underlined.

WVC	CZE[a]	ENG	ESP	EST	FIN[c]	HUN[c]	ISR	NOR	SCO[b]	SVN	SWE
All	**66,439**	**3779**	**97,688**	**23,951**	**26,259**	**11,520**	**8334**	**39,375**	**3324**	**31,237**	**333,590**
Roe deer *(C. capreolus)*		635	38,923	19,161	10,727	7733		28,808		25,008	247,040
Red deer *(C. elaphus)*		98	6347			1895		4890		587	2105
Fallow deer *(D. dama)*		2290	44		43	29				45	19,592
Moose *(A. alces)*				3114	3490			5677			32,199
Wild boar *(S. scrofa)*		383	52,374			1162	612			630	32,654
White-tailed deer *(O. virginianus)*					11,867						
Non-specified ungulates		373			132					44	
Red fox *(V. vulpes)*						178	1158			4923	
Golden jackal *(C. aureus)*							2645				
Other species				1676		523	3919				

[a] Roe deer and wild boar numbers were estimated as being 80% and 10%, according to the 2014–2016 dataset in which species determination was available, and Srazenazver.cz.

[b] Breakdown of SCO data by species are estimated as 75% roe deer, 20% red deer with remainder fallow and sika based on smaller regional sub-samples for which the species was accurately registered in the period 2015–2019. SCO data is only from the national strategic highways network, not from any more minor roads.

[c] Data from 1/2017 onward.

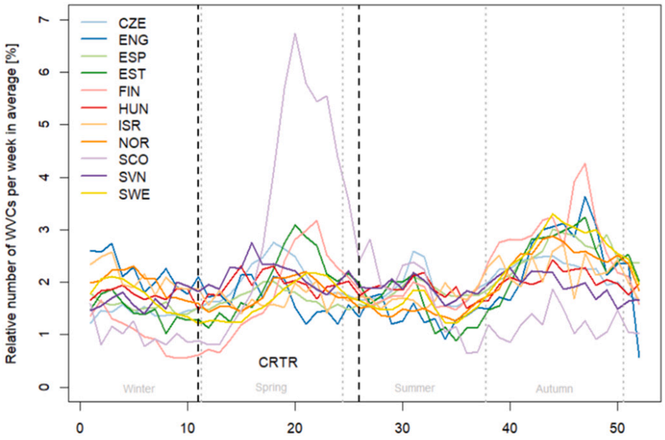

Fig. 1. An average weekly distribution of WVC (in %) aggregated over period 2015–2019 (2017–2019 for FIN and HUN) for the respective weeks. Vertical lines indicate the period of CRTR (11th – 26th week).

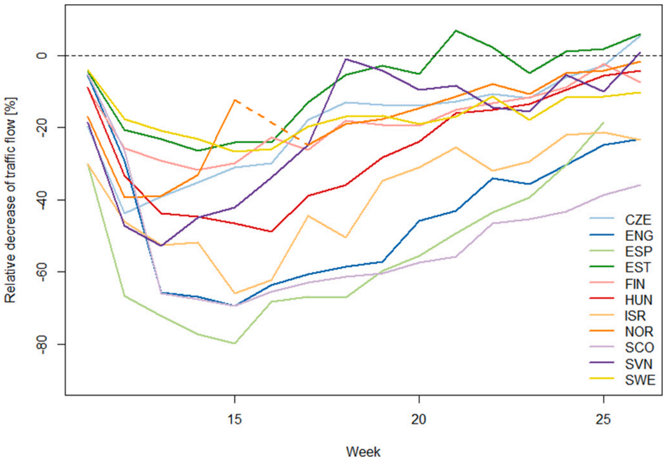

Fig. 2. Relative decrease (%) in traffic flow during the CRTR period for 11 countries in relation to the same week of 2019 (CZE, ESP, EST, FIN, HUN, NOR, SVN, SWE) or the 10th week of 2020 when records for 2019 were not available (ENG, SCO) or the 9th week (ISR; national holidays in the 10th). For a description of data see Appendix A. Data for week 16 in NOR were not available (we used linear interpolation of the neighbouring values, see the dashed part of the respective curve).

reporting RR, we report percentage reduction in WVC (= 100*(RR – 1)) as this shows more directly the effect on the number of WVC (see Fig. 4 and Table 2).

RR was calculated for periods of X^{th} week to Y^{th} week, where $X = 11$ (CZE, ESP, EST, FIN, HUN, ISR, NOR, SVN) or $X = 12$ (ENG, SCO, SWE; their CRTR period was one week shorter), and Y varies from X to 26. This seemingly increases the number of statistical tests. However, considering a particular country, if in period $X^{th} – Y^{th}$ week the null hypothesis is rejected, then it is very likely to also be rejected in following $X^{th} – (Y + 1)^{th}$ week. The correlated test statistics decrease the compound type I error in comparison with independent test statistics.

Since we are statistically evaluating eleven countries, it would be an option to apply some correction of the significance level (e. g. Bonferroni correction). However, such a correction would lead to inflating the type II error. Furthermore, the focus lies more in the effect sizes than in the *p*-values. In addition, the largest effect sizes within the time series are the least likely to be non-significant. Therefore, we only highlighted the maximum reduction of WVC per country and the situation in the entire CRTR period (Table 2). Other results serve to show how the percentage change in WVC varied over time (Fig. 4). Thus, we did not adjust the significance level.

3. Results

The observed number of WVC was significantly lower than predicted in seven of eleven countries throughout the CRTR period, varying from a reduction of 8.8% (NOR) to 37.4% (EST) (Table 2). In absolute numbers 17,461 WVC were recorded during CRTR in these countries, while 21,530 WVC would be expected under normal conditions, which corresponds to a total reduction of 18.9%. In four countries (SWE, ISR, SCO and ENG) we found no statistically significant difference between the observed and predicted number of WVC throughout the CRTR period (Table 2).

In all countries except SCO, we found a decrease in WVC during periods of one or more weeks throughout the whole CRTR period. The highest percentage reduction of more than 40% was found in EST, ESP, ISR and CZE during the first part of CRTR, while in the other countries it varied from about 17% to 33% (Fig. 4, Table 2).

4. Discussion

Compared to the expected numbers under normal conditions we showed that WVC was reduced with approximately 19% in 7 of 11 countries throughout the whole CRTR period but exceeded well above 20% and reached more than 40% in some countries during the first weeks of the lockdown. In all countries except one, we found a decrease

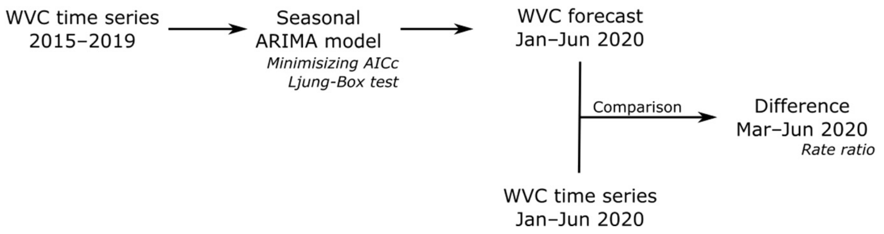

Fig. 3. A flow chart indicating the procedure of WVC difference estimation.

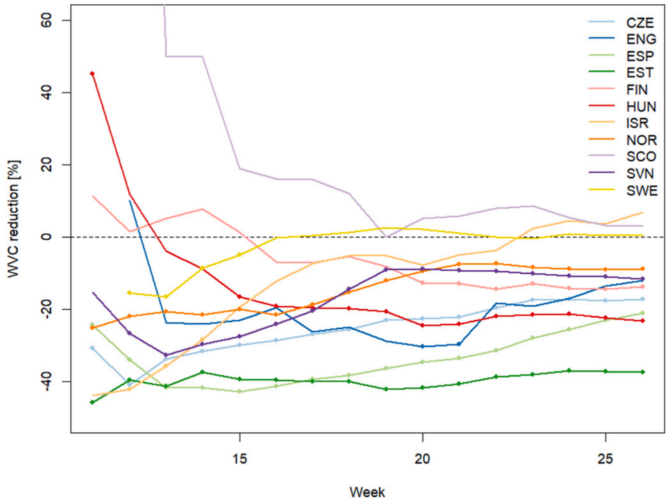

Fig. 4. An estimate of WVC reduction (%) during CRTR (11th–26th week in 2020) in relation to expected WVC. WVC reduction was calculated for periods of X^{th} week to Y^{th} week, where $X = 11$ (CZE, ESP, EST, FIN, HUN, ISR, NOR, SVN) or $X = 12$ (ENG, SCO, SWE; their CRTR period is one week shorter), and Y varies from X to 26. The dots represent statistically significant values. Detailed figures for each country can be found in Appendix C.

Table 2
Estimates of WVC change (%) during CRTR. Bold values are statistically significant on the standard level of significance (5%).

Country	The highest statistically significant decrease			Decrease in the entire CRTR period		
	Average WVC change per week	WVC change [%]	Period [week] *	WVC change	WVC change [%]	Period [week]
CZE	**−107**	**−41.0**	11–12	**−936**	**−17.3**	11–26
ENG	**−3**	**−30.4**	12–20	−17	−12.1	12–26
ESP	**−149**	**−42.9**	11–15	**−1231**	**−21.2**	11–26
EST	**−85**	**−45.9**	11–11	**−858**	**−37.4**	11–26
FIN	**−26**	**−14.5**	11–25	**−394**	**−13.8**	11–26
HUN	**−18**	**−24.6**	11–20	**−263**	**−23.2**	11–26
ISR	**−10**	**−42.2**	11–12	24	6.8	11–26
NOR	**−33**	**−25.2**	11–11	**−173**	**−8.8**	11–26
SCO	–	–	–	9	3.1	12–26
SVN	**−37**	**−32.7**	11–13	**−214**	**−11.7**	11–26
SWE	**−148**	**−16.7**	12–13	50	0.3	12–26

Note: For each country, a statistically significant result with the largest effect size was selected from Fig. 4 (see the first part of the Table, i.e. columns 2, 3 and 4). This Table highlights the most important results visualized in Fig. 4. * the second number of this interval corresponds to a week with the highest WVC decrease (compare with Fig. 4).

in WVC during periods of one or more weeks throughout the whole CRTR period.

4.1. The relationship between WVC and traffic volume

Our results are in line with previous studies demonstrating a positive but not necessarily always linear relationship between the number of WVC and traffic volume (e.g., Mysterud, 2004; Seiler, 2005; Rolandsen et al., 2011; Nelli et al., 2018; Bíl et al., 2020a). The highest percentage reduction in WVC were recorded during the first weeks of the CRTR (Fig. 4 and Table 2). Differences among countries are likely a consequence of both different lengths and the degree in the lockdown before restrictions were relaxed. In Spain, which was probably among the countries with the largest reductions in traffic, we also found one of the most significant reductions in WVC. In countries where traffic intensity seemed to return faster to the normal levels (e.g., SVN, NOR, FIN; see Fig. 2), however, we found a lower overall decline in WVC. This supports that the CRTR was the main reason for reduced WVC in Europe in spring 2020.

We did not include changes in traffic volume in the statistical analyses as the available data were incomplete, and in many cases only represented selected roads in each country. The traffic volume data was only included to serve as examples of change in traffic volume throughout the COVID-19 lockdown in the respective countries during CRTR (Appendix A). The weekly development in the traffic volume indices in each country showed a quite similar development during the CRTR period, with the largest reduction in the beginning and then a gradual increase towards the normal level (Fig. 2). The weekly development of WVC did not vary as consistently over time in all countries (Fig. 4). This different pattern in several countries between the decrease in traffic and WVC may reflect that the indices for traffic volume in several countries do not fully reflect the actual decrease in traffic on roads with the most WVC. The relationship between WVC and traffic volume can, however, also be non-linear (Seiler and Helldin, 2006; Rolandsen et al., 2011; Jacobson et al., 2016). That means that small or even moderate reductions in traffic volume need not necessarily cause a decrease in WVC.

The overlap between seasonal peaks in WVC (Fig. 1) and weekly reductions in traffic during CRTR may also have affected the decrease in WVC, for example, WVC peak in May in both ENG (Langbein, 2011) and SCO (Langbein, 2019), while the greatest decline in 2020 traffic occurred before week 16 (mid-May) in all countries included in the present study. By week 20, traffic had already returned again to over 75% of levels prior to CRTR. This may be an explanation as to why high traffic decline in SCO did not manifest itself in fewer WVC.

4.2. Study limitations

We acknowledge that our study has limitations. First, we did not include other confounding factors that vary temporally. For example, weather conditions and interannual variability in seasonal food availability may affect WVC over shorter time scales (weeks, months). In Finland, variation in moose population size and traffic volume explained only about 60% of the annual variation in the number of moose-vehicle collisions (Niemi et al., 2017), and Rolandsen et al. (2011) found a doubling in the number of moose-vehicle collisions in Norway between years of minimum and maximum snow depth after controlling for moose population size, traffic volume and temperature. This indicates that WVC numbers in north-European countries (particularly NOR and SWE) can be heavily influenced by snow cover. Moreover, variation in temperature and climate indices has been shown to be associated with a varying number of WVC (Mysterud, 2004; Rolandsen et al., 2011).

Second, our results rely on the assumption that the systems of WVC reporting in each of the countries included were sufficiently stable and remained homogenous over the whole study period 2015–2020, including the CRTR period. Therefore, we only worked with data not collected by citizen-science approaches, where data are often collected by volunteers that only report when they are on their regular routes to/from work (e.g., Bíl et al., 2020b), and are thus largely affected by COVID-19 lockdown measures.

Last, underreporting is a common issue in WVC data analyses (e.g., Bíl and Andrášik, 2020), and hence while available WVC statistics can often provide a good index of annual and seasonal changes in wildlife roadkill, they can only provide *minimum* estimates of absolute numbers. Across Europe, reliable data on WVC are available only for large mammals, mainly ungulates. In this study, however, the primary aim was to focus on ratios (i.e., the decrease of WVC in the CRTR period in comparison with predictions based on data from previous years), presuming that WVC recording remained more or less the same in 2020 as in past years. Therefore, our results should not be affected by underreporting. However, due to an unknown proportion of WVC that is not reported in each country, we cannot determine the absolute changes in WVC. Our results only provide estimates on the percentage reduction in WVC, and a minimum number of animals likely to have survived as a result of CRTR.

4.3. The importance and the effect of CRTR to wildlife conservation

As presented above, at least 4069 fewer large wild mammals were killed by cars during CRTR than would be expected during that period in a normal year. This number presents, however, only a small proportion of all wild animals that have survived as a direct result of these unique traffic conditions and thus benefited from CRTR. Apart from studied taxa, for which reliable data are available (primarily ungulates, and to a lesser extent also mesocarnivores), there are also many other species which could not be included in our study. It is evident that any quantification of the comprehensive impacts of vehicular transport to wildlife strongly relies on reliable roadkill data.

This situation of WVC worldwide is alarming, but relevant and comprehensive data are still missing in many countries. This is why this study was only performed in eleven countries where relevant data could be accessed quickly, with information available generally dominated by WVC with large and relatively abundant mammalian species. However, WVC reporting systems, usually with high volunteer (i.e., citizen-scientists) participation, are increasingly being introduced in many countries (Bíl et al., 2020b; Schwartz et al., 2020; Shilling et al., 2020, 2021), which may assist in a better understanding of trends in WVC even if not total numbers in the future.

Traffic calming, due to CRTR, resulted in reduced traffic-induced mortality in wild animals. This is also likely to lead to increased survival and possibly larger wildlife populations. Therefore, local and temporarily limited traffic flow reduction, particularly in areas where the focus is on conservation of endangered species, may be an option to mitigate wildlife roadkills (van Langevelde and Jaarsma, 2009).

5. Conclusions

We demonstrate a marked reduction in WVC in countries across Europe and Israel during COVID-19 lockdown in spring 2020, which is primarily believed to be due to a reduction in road traffic. Similar results are shown in a study from the United States (Shilling et al., 2021). These studies show the negative effect of road traffic on wildlife, and how wildlife benefited from travel restrictions and reduced traffic demand in relation to the COVID-19 pandemic. The reduced number of WVC most likely led to the survival of many wild animals which would, in all probability, have been killed by cars under normal traffic conditions. Future efforts to mitigate WVC are beneficial both from a wildlife conservation and human safety perspective. WVC data of sufficient quality, from several different species and countries, would provide a better basis to achieve this.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109076.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like express our thanks to WVC and traffic flow data providers, namely: Hunters Association of Slovenia for developing an on-line hunting information system enabling us to access comprehensive data on WVC in Slovenia, and Tatjana Bubnič (Slovenian Road Agency) for traffic volume data; The Israeli Nature and Parks Authority (INPA); Gal Vine, for providing the roadkill data; Decell Technologies LTD; Tuval Stone, and The Israel Central Bureau of Statistics; Benyamin Fenesh, for providing national traffic volume data; Traffic Police Department of the National Police Headquarters in Hungary, Hungarian Public Road Nonprofit Pte Ltd. Co.; UK WVC up to end 2019 were gathered during a number of research projects by Highways England for England, and in Scotland by Scottish Natural Heritage. M. Kruuse gratefully acknowledges Villu Lükk from Estonian Road Administration for providing the wildlife collision data and Tanel Jairus from Teede Tehnokeskus AS for providing national road traffic statistics; General Directorate of Traffic of the Spanish Minister of Interior, for providing the wildlife collision and national traffic volume data; The Swedish National Council for Wildlife accidents and the Swedish Police for providing accident statistics; and the Swedish Transport Administration for data on traffic flows; The Finnish WVC data collection organized by Game Management Associations and conducted by voluntary hunters is highly appreciated; to wildlife managers in Norway who have reported WVC data to the national database owned by the Norwegian Environment Agency. We would like to thank our partners from other countries (Sarah MacDougall, Casey Visintin, Te-En Lin, Nikica Šprem, and Fernanda Abra), who provided us with their roadkill data, but finally those WVC data were not used in the current analyses. We further thank Rachel Langbein and David Livingstone for assistance with final editing of English. We would also like to thank Richard B. Primack and three anonymous reviewers whose comments increased the lucidity of the text.

Funding

M. Bíl, V. Cícha and R. Andrášik worked with the financial support of the Ministry of Transport, Czech Republic within the program of long-term conceptual development of research institutions on the research infrastructure acquired from the Operation Program Research and Development for Innovations (CZ.1.05/2.1.00/03.0064). B. Pokorny acknowledges the financial support from the Ministry of Agriculture, Forestry and Food of the Republic of Slovenia, and the Slovenian Research Agency (project V4–1825; programme group P4–0107).

References

Bates, A.E., Primack, R.B., Moraga, P., Duarte, C.M., 2020. COVID-19 pandemic and associated lockdown as a “Global Human Confinement Experiment” to investigate biodiversity conservation. Biol. Conserv. 248, 108665. https://doi.org/10.1016/j.biocon.2020.108665.

Bíl, M., Andrášik, R., 2020. The effect of wildlife carcass underreporting on KDE+ hotspots identification and importance. J. Environ. Manag. 275, 111254. https://doi.org/10.1016/j.jenvman.2020.111254.

Bíl, M., Kubeček, J., Sedoník, J., Andrášik, R., 2017. Srazenazver.cz: A system for evidence of animal-vehicle collisions along transportation networks. *Biol. Conserv. 213PA,* pp. 167–174. https://doi.org/10.1016/j.biocon.2017.07.012.

Bíl, M., Kubeček, J., Andrášik, R., 2020a. Ungulate-vehicle collision risk and traffic volume on roads. Eur. J. Wildl. Res. 66, 59. https://doi.org/10.1007/s10344-020-01397-8.

Bíl, M., Heigl, F., Janoška, Z., Vercayie, D., Perkins, S.E., 2020b. Benefits and challenges of collaborating with volunteers: examples from National Wildlife Roadkill Reporting Systems in Europe. J. Nat. Conserv. 54C, 125798. https://doi.org/10.1016/j.jnc.2020.125798.

Bissonette, J. A., Kassar, C. A., Cook, L. J., 2008. Assessment of costs associated with deer–vehicle collisions: human death and injury, vehicle damage, and deer loss. Human–Wildlife Interactions: 2, 1, Article 9. DOI: 10.26077/ns32-mk60.

Chapron, G., et al., 2014. Recovery of large carnivores in Europe’s modern human-dominated landscapes. Science 346, 1517–1519. https://doi.org/10.1126/science.1257553.

Corlett, R.T., Primack, R.B., Devictor, V., Maas, B., Goswami, V.R., Bates, A.E., Koh, L.P., Regan, T.J., Loyola, R., Pakeman, R.J., 2020. Impacts of the coronavirus pandemic on biodiversity conservation. Biol. Conserv. 246, 108571.

Faragó, S., László, R, 2017. Magyar Vadelhullás monitoring, 2015/2016 vadászati év. Monitoring jelentés (Hungarian Wildlife Mortality Monitoring, 2015/2016 Hunting Year. Monitoring report) University of Sopron, pp. 71.

Forman, R.T., Alexander, L.E., 1998. Roads and their major ecological effects. Annu. Rev. Ecol. Syst. 29, 207–231.

Garrote, G., Fernández-López, J., López, G., Ruiz, G., Simón, M.A., 2018. Prediction of Iberian lynx road–mortality in southern Spain: a new approach using the MaxEnt algorithm. Anim. Biodivers. Conserv. 41 (2), 217–225. https://doi.org/10.32800/abc.2018.41.0217.

Grilo, C., Koroleva, E., Andrášik, R., Bíl, M., Gonzalez-Suarez, M., 2020. Roadkill risk and vulnerability in European birds and mammals. Front. Ecol. Environ. 18 (6) https://doi.org/10.1002/fee.2216.

Hothorn, T., Brandl, R., Müller, J., 2012. Large-scale model-based assessment of deer–vehicle collision risk. PLoS One 7 (2), e29510, 10.1371. https://doi.org/10.1371/journal.pone.0029510.

Hothorn, T., Müller, J., Held, L., Möst, L., Mysterud, A., 2015. Temporal patterns of deer–vehicle collisions consistent with deer activity pattern and density increase but not general accident risk. Accid. Anal. Prev. 81, 143–152.

Hyndman, R., Athanasopoulos, G., Bergmeir, C., Caceres, G., Chhay, L., O’Hara-Wild, M., Petropoulos, F., Razbash, S., Wang, E., Yasmeen, F., 2020. Forecast: forecasting functions for time series and linear models. R package version 8.13. https://pkg.robjhyndman.com/forecast/.

Hyndman, R.J., Athanasopoulos, G., 2018. Forecasting: Principles and Practice, 2nd edition. Melbourne, Australia, OTexts.

Jacobson, S., Bliss-Ketchum, L., De Rivera, C., Smith, W. P., 2016. A behavior based framework for assessing barrier effects to wildlife from vehicle traffic volume. Ecosphere 7:article e01345 doi:Ecosphere 7(4):e01345. https://doi.org/10.1002/ecs2.1345.

Jägerbrand, A.K., Gren, I-M., Seiler, A., Johansson, Ö., 2018. Uppdatering och nya effektsamband i effektmodellen för viltolyckor. (Update on and new cause-effect relationships in wildlife-vehicle collision models). Calluna reports 2018-04-03. Calluna AB, Linköping, Sweden. http://www.calluna.se/userfiles/files/6_Uppdatering_effektmodell_viltolyckor_2018.pdf.

Kruuse, M., Enno, S-E., Oja, T. 2017, May 14–18. Using available existing data for analysing temporal patterns of traffic collisions related to large ungulates. [Conference poster presentation]. ICOET - The 2017 International Conference on Ecology & Transportation, Salt Lake City, UT, USA. DOI: 10.13140/RG.2.2.26896.61440.

Langbein J., 2011. Monitoring reported deer road casualties and related accidents in England to 2010. The Deer Initiative, Wrexham, UK. Research Report 2011/3. http://www.deercollisions.co.uk/ftp/DI%20England%20Monitoring%20DVCs%20to%202010/DI-DVC_England2011_Main_final_rev.pdf.

Langbein, J., 2019. Deer-vehicle collision (DVC) data collection and analysis 2016–2018. Scottish Natural Heritage Research Report No. 1158. https://www.nature.scot/naturescot-research-report-1158-deer-vehicle-collision-dvc-data-collection-and-analysis-2016-2018.

Langbein, J., Putman, R., Pokorny, B., 2011. Traffic collisions involving deer and other ungulates in Europe and available measures for mitigation. In: Putman, R., Apollonio, M., Andersen, R. (Eds.), Ungulate Management in Europe: Problems and Practices. Cambridge University Press, Cambridge, pp. 215–259.

Linnell, J.D.C., Cretois, B., Nilsen, E.B., Rolandsen, C.M., Solberg, E.J., Veiberg, V., Kaczensky, P., Van Moorter, B., Panzacchi, M., Rauset, G.R., Kaltenborn, B., 2020. The challenges and opportunities of coexisting with wild ungulates in the human-dominated landscapes of Europe’s Anthropocene. Biol. Conserv. 244, 108500. https://doi.org/10.1016/j.biocon.2020.108500.

Mysterud, A., 2004. Temporal variation in the number of car-killed red deer Cervus elaphus in Norway. Wildl. Biol. 10, 203–211. https://doi.org/10.2981/wlb.2004.026.

Nelli, L., Langbein, J., Watson, P., Putman, R., 2018. Mapping risk: quantifying and predicting the risk of deer-vehicle collisions on major roads in England. Mamm. Biol. 91, 71–78. https://doi.org/10.1016/j.mambio.2018.03.01.

Niemi, M., Rolandsen, C.M., Neumann, W., Kukko, T., Tiilikainen, R., Pusenius, J., Solberg, E.J., Ericsson, G., 2017. Temporal patterns of moose-vehicle collisions with and without personal injuries. Accid. Anal. Prev. 9898, 167–173. https://doi.org/10.1016/j.aap.2016.09.024.

Oslis, 2020. Osrednji slovenski lovsko-informacijski sistem. http://oslis.gozdis.si/ (in Slovene).

Pagany, R., 2020. Wildlife-vehicle collisions – influencing factors, data collection and research methods. Biol. Conserv. 251, 108758.

Palazón, S., Melero, Y., Gómez, A., López de Luzuriaga, J., Podra, M., Gosàlbez, J., 2012. Causes and patterns of human-induced mortality in the critically endangered European mink Mustela lutreola in Spain. Oryx 46, 614–616. https://doi.org/10.1017/S0030605312000920.

Pokorny, B., 2006. Roe deer–vehicle collisions in Slovenia: situation, mitigation strategy and countermeasures. Veterinarski Arhiv 76, 177–187.

Putman, R., Appolonio, M., Andersen, R. (Eds.), 2011. Ungulate Management in Europe: Problems and Practices. Cambridge University Press.

Rolandsen, C.M., Solberg, E.J., Herfindal, I., Van Moorter, B., Sæther, B.-E., 2011. Large-scale spatiotemporal variation in road mortality of moose: is it all about population density? Ecosphere 2, 1–12. https://doi.org/10.1890/ES11-00169.1.

Rutz, C., Loretto, M.-C., Bates, A.E., Davidson, S.C., Duarte, C.M., Jetz, W., Johnson, M., Kato, A., Kays, R., Mueller, T., Primack, R.B., Ropert-Coudert, Y., Tucker, M.A., Wikelski, M., Cagnacci, F., 2020. COVID-19 lockdown allows researchers to quantify the effects of human activity on wildlife. Nat. Ecol. Evol 4, 1156–1159. https://doi.org/10.1038/s41559-020-1237-z.

Schwartz, A.L.W., Shilling, F.M., Perkins, S.E., 2020. The value of monitoring wildlife roadkill. Eur. J. Wildl. Res. 66, 18. https://doi.org/10.1007/s10344-019-1357-4.

Seiler, A., 2005. Predicting locations of moose-vehicle collisions in Sweden. J. Appl. Ecol. 42, 371–382. https://doi.org/10.1111/j.1365-2664.2005.01013.x.

Seiler, A., Helldin, J.O., 2006. Mortality in wildlife due to transportation. In: Davenport, J., Davenport, J.L. (Eds.), The Ecology of Transportation: Managing Mobility for the Environment. Kluwer, Amsterdam, pp. 165–190. https://doi.org/10.1007/1-4020-4504-2_8.

Seiler, A., Willebrand, S., Olsson, M., Wahlman, H., 2019. Viltolyckskartor - Teknisk beskrivning för datahantering och produktion. (Wildlife-vehicle accident maps - technical description for data management and production.). Swedish Transport Administration, Publication 179, TVD-52097. Borlänge, Sweden. http://trafikverket.diva-portal.org/smash/record.jsf?pid=diva2%3A1366843&dswid=-5498.

Shilling, F., Collinson, W., Bil, M., Vercayie, D., Heigl, F., Perkins, S.E., MacDougall, S., 2020. Designing wildlife-vehicle conflict observation systems to inform ecology and transportation studies. Biol. Conserv. 251, 108797. https://doi.org/10.1016/j.biocon.2020.108797.

Shilling, F., Nguyen, T., Saleh, M., Kyaw, M., Tapia, K., Trujillo, G., Bejarano, M., Waetjen, D.P., Peterson, J., Kalisz, G., Sejour, R., Croston, S., Ham, E., 2021. A Reprieve from US Wildlife Mortality on Roads during the COVID-19 Pandemic. Biol. Conserv. 256, 109013.

Solberg, E.J., Rolandsen, C.M., Herfindal, I., Heim, M., 2009. Moose and deer-vehicle accidents in Norway during the period 1970-2007. NINA Report 463 (In Norwegian with English summary).

van Langevelde, F., Jaarsma, C.F., 2009. Modeling the effect of traffic calming on local animal population persistence. Ecol. Soc. 14 (39).