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Exploring 15 years of brown bear (*Ursus arctos*)-vehicle collisions in northwestern Greece

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Abstract

Road networks provide several benefits to human societies; however, they are also one of the major drivers of fragmentation and habitat degradation. Their negative effects include wildlife-vehicle collisions which are associated with increased barrier effects, restricted gene flow, and increased local extinction risk. Large carnivores, such as the brown bear (*Ursus arctos*), are vulnerable to road mortality while they also put human safety at risk in every collision. We recorded approximately 100 bear-vehicle collisions during the last 15 years (2005–2020) in northwestern Greece and identified common aspects for collisions, i.e., spatial, or temporal segregation of collision events, road features, and age or sex of the involved animals. We recorded collisions in both the core distribution area of brown bears, as well as at the periphery, where few individuals, mostly males, disperse. According to our findings, there are four collision hotspots which include ca. 60% of total collisions. Bear-vehicle collisions occurred mostly in periods of increased animal mobility, under poor light conditions and low visibility. In most cases, we deem that a collision was unavoidable at the time of animal detection, because the driver could not have reacted in time to avoid it. Appropriate fencing, in combination with the retention of safe passages for the animals, can minimize collisions. Therefore, such mitigation measures, wildlife warning signs and other collision prevention systems, such as animal detection systems, should be adopted to decrease the number of bear-vehicle collisions and improve road safety.

Keywords

Collision patterns, *Ursus arctos*, wildlife-vehicle collisions

Introduction

Globally, road networks are expanding at an unprecedented rate (Alamgir et al. 2017). The total length of roads already exceeds 64 million km (van der Ree et al. 2015) and by 2050, at least 25 million km of additional roads are expected to be built (Laurance et al. 2014). Transportation infrastructure promotes economic growth and human welfare (Kati et al. 2020), thus the majority of new roads (ca. 90%) will be constructed in developing nations (Alamgir et al. 2017). On the other hand, roads are also one of the most important drivers of landscape fragmentation, habitat degradation and biodiversity loss (van der Ree et al. 2011; Ceia-Hasse et al. 2018). Road effects include edge and barrier effects (Trombulak and Frissell 2000), as well as extensive wildlife mortality due to collisions with vehicles (Barbosa et al. 2020).

Wildlife–vehicle collisions are among the most important road effects to wildlife as their impact reaches far beyond the kill (Ascensão et al. 2013). They are the most pronounced and well documented road effect (Grilo et al. 2009; Ascensão et al. 2017) and a significant threat for several species; in some cases, roadkill is the main cause of human-related mortality (Forman and Alexander 1998), e.g., the case of the barn owl (*Tyto alba*) (Fajardo 2001), and the Iberian lynx (*Lynx pardinus*) in Doñana, Spain (Ferreras et al. 1992). The needs of large carnivores for broad, relatively undisturbed areas and their low reproductive rates render them vulnerable to road effects, and especially to road-related mortality (Rytwinski and Fahrig 2011). As such, the brown bear (*Ursus arctos*) population is negatively affected in a much larger range than the road segment where collisions occur (Kaczensky et al. 2003). Wildlife-vehicle collisions can reduce effective population sizes and gene flow, influence local population dynamics, and increase demographic structure (Ramp and Ben-Ami 2006; Balkenhol and Waits 2009). High traffic volumes restrict animal movement (Northrup et al. 2012; Skuban et al. 2017), while road mortality also entails a barrier effect and decreased landscape connectivity and thus, may lead to loss of genetic variation through genetic drift (Jackson and Fahrig 2011). These effects may lead to populations bottlenecks (Straka et al. 2012) and decrease the probability of a population's long-term survival, with local populations being prone to extinction due to stochastic events (Balkenhol and Waits 2009; Ascensão et al. 2013).

The brown bear is an emblematic species and strictly protected large carnivore species in most European countries and is listed in Annex II and IV of the EU Habitats Directive (92/43/EEC). In Greece, brown bears reach their southern-most distribution in Europe (Karamanlidis et al. 2018). The species is found in two disjunct subpopulations: the eastern population nucleus in the Rhodope complex and the western population nucleus in the Pindos – Peristeri mountain ranges (Mertzanis 1994; Mertzanis et al. 2008). The two subpopulations have cross-border connections with the Eastern Balkans and the Dinaric-Pindus populations respectively (Chapron et al. 2014; Boitani et al. 2015). The species is protected under both national and international legislation. Consistent with the large carnivore population recovery in Europe (Chapron et al. 2014), brown bears exhibited a remarkable demographic and range recovery in Greece and the species now counts approximately 500 individuals (Karamanlidis et al. 2015; Pylidis et al. 2021). Yet, threats and pressures remain, and specific measures must be adopted to guarantee the species' long-term survival (Mertzanis et al. 2009; Karamanlidis et al. 2021). Bear-vehicle collisions (BVCs) have often made the news over the past few years, raising both conservation and road safety issues (Kaczensky et al. 2003). In this study, we explored the spatial and temporal patterns of BVCs in Greece. We used BVC data that occurred during a 15-year period (2005–2020) and attempted to detect collision hotspots and factors that increase collision risk. In this context, we mapped seasonal and daily peaks, and their relation to the age and sex of involved individuals, as well as to the different ecological seasons of bears. Furthermore, we explored the characteristics of the road network and BVC location such as spatial extent, speed limit, and viewshed to identify conditions that might be linked to increased BVC risk, and calculated an average vehicle's stopping distance in an attempt to discern between high and low risk locations.

Methods

Study area

The study area coincides with the species' range in Greece (distribution area: 24,500.3 km^2, Fig. 1a). The landscape exhibits great heterogeneity, varying from natural and semi-natural areas to human dominated landscapes. Thus, a mosaic of different habitats, such as broadleaf and coniferous forests, shrublands and grasslands, agricultural and artificial lands, characterizes the study area.

Data collection and analysis

We collected data on BVCs for the past 15 years (2005–2020), with the Bear Emergency Team being the main source of information. The Bear Emergency Team deals with human-bear interference incidents and operates under the official "Bear-human proximity and interference Management Protocol" operational manual with the endorsement of the state. However, there are several cases of BVCs that remain unrecorded as they were not reported to the authorities, usually because property damage was minor, and the injured animal fled. We included a handful of such incidents in our database, recorded after coincidental personal communication with the people involved.

For every BVC, event-level information (location, date, and time of incidence) and individual-level information (sex and age of the animal, and number of injured animal) were recorded. We explored the spatial distribution of BVCs and spotted areas of high BVC density, by applying the kernel density method and visualizing density by a heatmap with the function 'heatmap' of ArcGIS Pro (ArcGIS Software by ESRI). For every area that showed high BVC density, we calculated the length of roads where BVCs have occurred, the convex hull area, and road density (road length/convex hull area). Furthermore, we explored how the incidences are distributed across the biologically meaningful seasons for brown bear activities, as described by de Gabriel Hernando et al. (2020): “emergence” (1 March–21 April), “mating” (22 April–21 June), “post-mating” (22 June–7 August), “early hyperphagia” (8 August–7 October) and “late hyperphagia” (8 October–15 December) season. For each BVC location, we obtained weather data (Visual Crossing Corporation 2021) and also sunrise and sunset times (Hoffmann 2021) to identify conditions (e.g., rainy conditions or night) favoring BVC.

We explored how characteristics of road network and location are linked to BVCs. We also derived road network vector data in our study area (Geofabrik GmbH and OpenStreetMap Contributors 2020) and recorded, per case, the speed limit imposed by the national Highway Code or by local signage. Then, we calculated per case an average vehicle’s stopping distance following the guidelines of the “American Association of State Highway and Transportation Officials” and taking into account weather conditions to detect road surface wetness. Viewshed per BVC location was also estimated within a 1 km buffer zone using the digital surface model produced in the framework of the Reference Data Access (RDA) Action of the EU GMES/Copernicus program (Copernicus Land Monitoring Services 2020). Based on the estimated viewshed at both sides of the BVC location, we calculated the mean distance where a driver could have spotted the animal on the road (sight distance) and juxtaposed it to stopping distance, as estimated per incident, to identify cases where a BVC might have been avoided (low risk locations). Accordingly, we consider high risk the locations where vehicles are not able to stop in time and avoid the BVC as the sight distance is shorter than the stopping distance. Lastly, we calculated the visibility index (visible length/ total length of the road segment) within the 1 km buffer zone. All the calculations were performed with the ArcMap 10.7 and ArcGIS Pro (ArcGIS Software by ESRI).

Results

A total of 101 BVCs were recorded between 2005 and 2020, with all incidences occurring in the western bear population nucleus in the Pindos – Peristeri mountain ranges. Annual BVC-attributable mortality corresponds to approximately 1.2% of the total population with the mean annual number of BVCs being 6.3 ± 4 (min = 1 in 2006, max = 16 in 2012). Among the involved individuals, 30 were female and 38 male bears, while in 33 individuals the sex was not identified. Ages of the bears varied from 4 months old up to ca. 25 years of age. Specifically, 39 individuals were adults (>4 years old), 17 subadults (1.5–4 years old), 17 cubs (<1.5 years old) and 28 were bears whose age has not been recorded. In only one case two animals, an adult female with a cub, were involved in a single collision.

We identified four areas with high BVC density (Fig. 1b): a) between the Vernon and Gramos mountains, at the outskirts of Kastoria and between the neighboring villages (location H1), b) at the western foothills of mount Askio (location H2), c) south

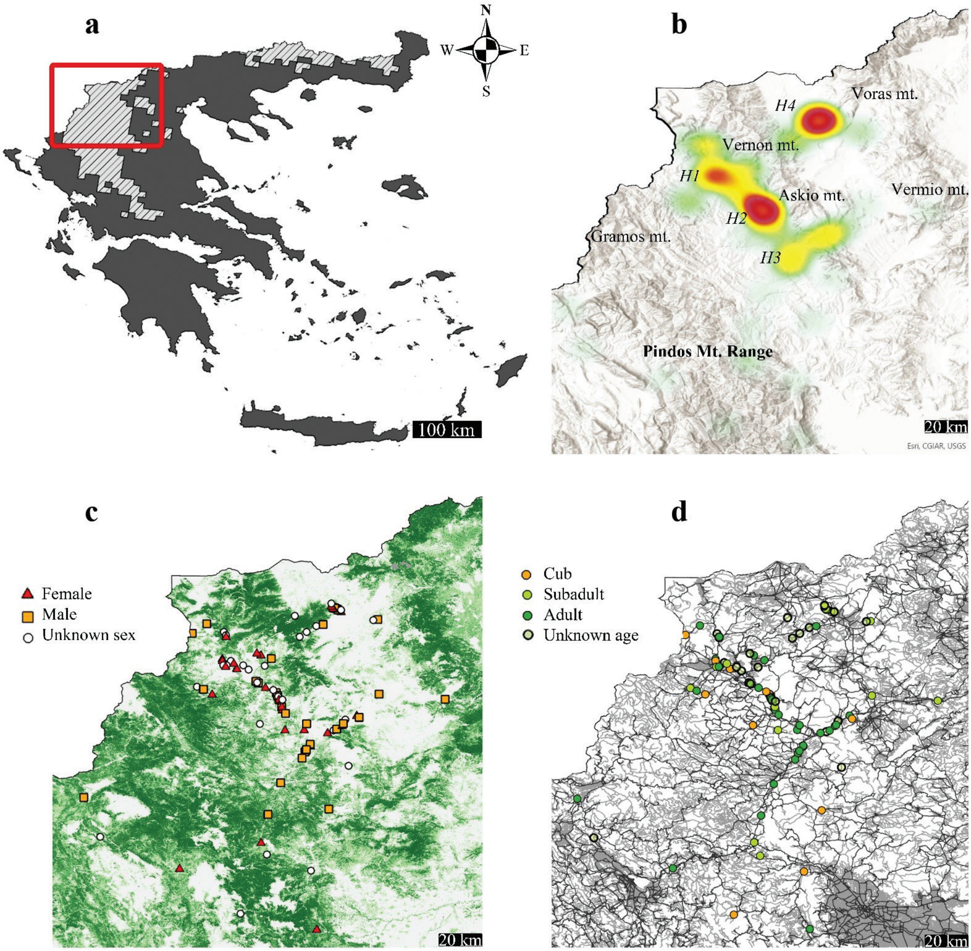

Figure 1. a Brown bear distribution in Greece is presented with a hatch pattern against a dark background **b** BVC heatmap and the main mountains in northwestern Greece **c** BVCs by sex with a tree cover density basemap (Copernicus Land Monitoring Services 2020 **d** BVCs by age class with a road network basemap (Geofabrik GmbH and OpenStreetMap Contributors 2020)

of mount Askio (location H3) and, d) between the Vernon and Voras mountains (location H4) (Table 1). Significantly, there have been some BVCs at the periphery of bear core habitat and distribution where mostly male bears were hit by vehicles, e.g., BVC at the southern foothills of mount Vermio. By contrast, in core habitat areas and areas characterized by increased human presence, i.e., proximity to towns and/or in more densely populated areas, we found that mostly females and young bears were hit by vehicles (Fig. 1c, d). For instance, at location H1 which exhibits the highest road density (Table 1) and is covered by discontinuous urban fabric, six female bears and five bears of unknown sex were involved in BVCs, out of which three were cubs, three subadults, two adult and three bears of unknown age. Finally, in location H4, at least 16 BVCs

Table 1. Details on the four high bear-vehicle collision (BVC) density locations (H1–H4) in northwestern Greece, in terms of BVC number and the area's road network (description of the BVC related road segments, total length of road segments where BVCs occurred, convex hull area, road density).

Location	Number of BVCs	Description of the BVC related road segments	Total length of road segments where BVCs occurred (km)	Convex hull area (km^2)	Road density (km/km^2)
H1	11	Secondary road complex	40.7	16.8	6.8
H2	18	A 15 km motorway segment & adjacent old national network segments	22.4	16.5	2.6
H3	14	A 32 km motorway segment & an adjacent secondary road segment	39.8	57.8	1.9
H4	16	A 4 km national road segment & 1 km of the adjacent old network	5	2.9	1

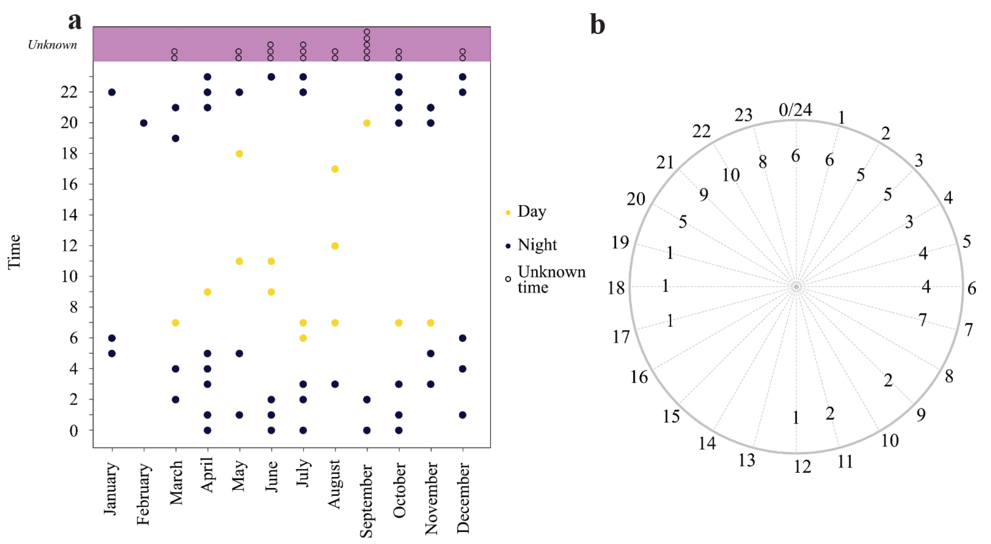

Figure 2. a BVCs across month of the year and time of day. Yellow indicates BVCs that occurred during daytime and dark blue the ones that occurred during the night, considering sunrise and sunset time by location. BVCs whose time of occurrence has not been recorded, are presented in the purple bar at the top of the figure **b** a clocklike figure where inner values indicate count of BVCs per time of day.

occurred during the past 15 years, which comprise of four collisions with females, seven with males and five with bears of unknown sex. In terms of age, they involved three cubs, five subadults, three adults and five bears of unknown age.

The 77% of BVCs occurred during the night (Fig. 2) and ca. 38% was associated to rainy weather. Most BVCs occurred in autumn (35%), followed by summer (28%), spring (26%) and lastly, winter (10%). The maximum number of BVCs took place in October (16 BVCs) (Fig. 2a).

When analyzed across the biologically defined seasons for bears, BVCs peak during late hyperphagia (n = 19) and mating (n = 18) and reach a minimum count of 6 during denning season. More males than females were involved in BVCs (23 males out of 35

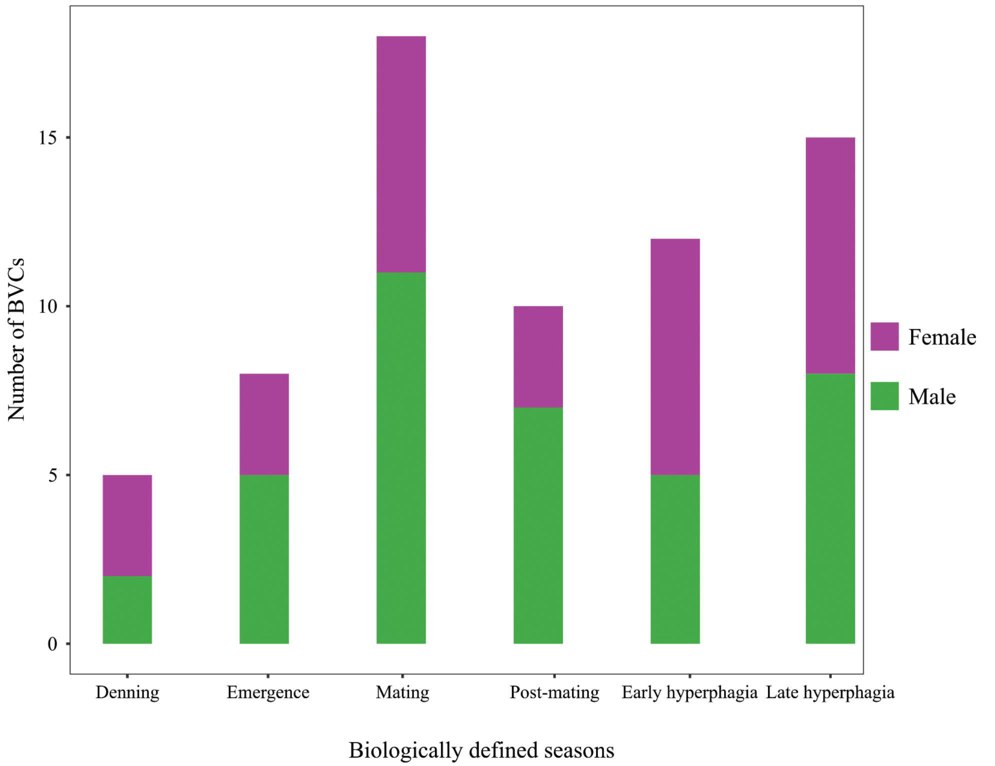

Figure 3. Number of BVCs per sex, across biologically defined seasons.

Table 2. Descriptive statistics for the estimated stopping distance, sight distance (estimated using the viewshed per location) and visibility index (calculated as visible length/total length of the road segment) for the 101 bear-vehicle collisions recorded.

	Mean	Minimum	Maximum
Stopping distance (m)	131.0 ± 76.1	25.7	304.9
Sight distance (m)	198.5 ± 159.8	2.4	865.7
Visibility index	0.3 ± 0.2	0.01	1

collisions) during emergence, mating, and post-mating seasons, whereas more females were involved during early and late hyperphagia (15 females out of 27 collisions) (Fig. 3).

Regarding the road characteristics at the collision point, the estimated mean stopping distance was smaller than the mean sight distance, i.e., the driver could potentially see the bear, react in time, and avoid the collision (Table 2). However, considering each case individually, we found larger stopping distances in 68% of the incidents, rendering those BVCs unavoidable for the drivers and the road segment as a high-risk location (Fig. 4). Furthermore, the visibility index at the locations where BVCs have occurred was generally low, and only 30% of the segment on average was visible due to the terrain.

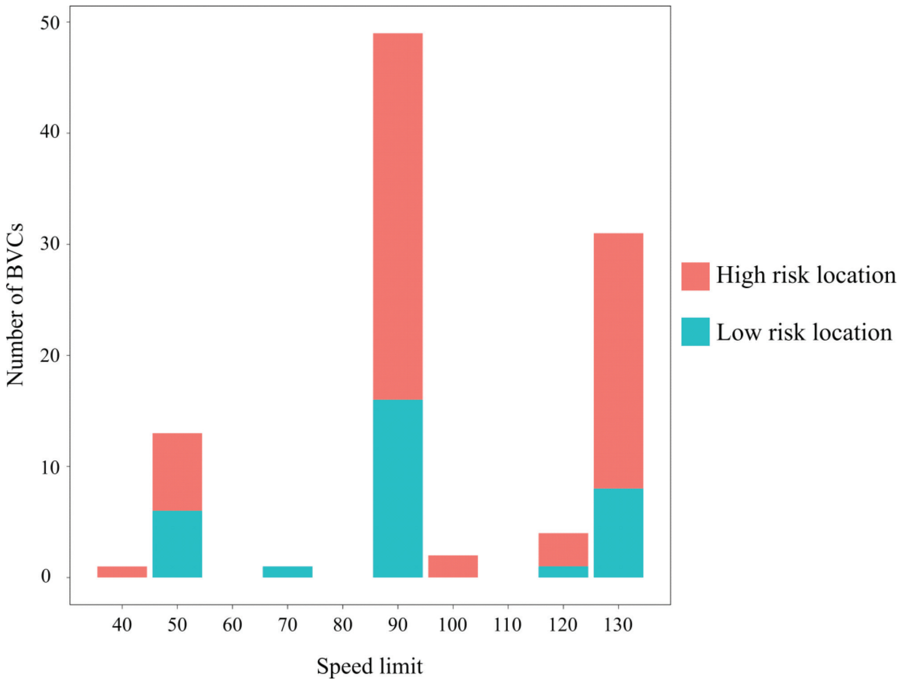

Figure 4. BVC counts across legal speed limits. Red indicates BVC counts in high-risk locations, where the collisions may have been unavoidable according to the sight distance set against the stopping distance, whereas blue marks BVC counts in low risk locations.

Discussion

Our results showed that at least 100 brown bears have been involved in BVCs over the last 15 years. We detected four collision "hotspots" in the western nucleus of bear population of Greece, located in the Pindos – Peristeri mountain ranges. Each of these areas is unique in terms of extent, road types and density, as well as the profile BVC victims. Furthermore, we found distinct temporal patterns pervading the collisions, which are linked to both driving conditions and the species' seasonal and circadian activity. Hence, we found that drivers are more likely to be involved in BVCs during late spring and fall when mating and hyperphagia take place. BVCs also seem to be linked to low visibility conditions which relate to both the terrain characteristics and low light conditions. Lastly, our results suggest that in most cases, it may not have been possible for the driver to react in time and thus, the collision was unavoidable.

Brown bear daily activity patterns have been well documented and in southern Europe the species demonstrates mainly a crepuscular and nocturnal activity pattern (Roth and Huber 1986; Clevenger et al. 1990; Kaczensky et al. 2006; de Gabriel Hernando et al. 2020), with human activity having a strong effect on circadian habitat use (Naves et al. 2001). The increased BVC risk during the night found here was possibly due to the species' nocturnal activity coupled with low light driving, when visibility is limited, and reaction times are longer (Eloholma et al. 2006).

BVC seasonal patterns were consistent to the species' life-history phenology and, like other carnivores, increased collisions were linked with higher mobility periods (Grilo et al. 2009). Both bear circannual activity and BVC number peaked in late spring and fall, i.e., mating and hyperphagia (Clevenger et al. 1990; Mertzanis 1994; García-Rodríguez et al. 2020) ecological seasons (de Gabriel Hernando et al. 2020). Bears exhibit a roam-to-mate behavior (Steyaert et al. 2012), thus both sexes increase their home ranges, and consequently road crossings during mating. Home ranges decrease during post-mating for both male and females without cubs (Dahle and Swenson 2003) and re-increase during hyperphagia (de Gabriel Hernando et al. 2020), when individuals become again more mobile in order to locate suitable resources, store fat and ultimately prepare for denning and reproduction (Ordiz et al. 2016; Sergiel et al. 2020). However, the two sexes do not cross roads equally (Sawaya et al. 2014) and crossing intensity changes seasonally (Guthrie 2012). Males cross roads more intensively during mating while searching for mates, whereas females increase road crossings during hyperphagia (Guthrie 2012) and as a result, BVCs also follow this pattern (Fig. 3).

The overlap of wildlife road crossing activity with other conditions increasing collision risk, such as poor light and road surface conditions can be considered the recipe for collision hotspots (Neumann et al. 2012). The majority of BVCs occurred under low conspicuity conditions (77%), and at locations where the average vehicle's stopping distance was larger than the sight distance (ca. 70%). Yet, considering that most drivers feel safe surpassing the legal speed limit (Mannering 2009), it is safe to assume that more than 70% of BVCs were already unavoidable when the driver detected the animal on the road. Such speed limit compliance issues render speed limit reduction a collision prevention measure of mixed effectiveness (Huijser and McGowen 2010).

We identified four BVC hotspots which include 58% of the total collisions. At location H1, which is dominated by humans and is characterized by high road density, we found mainly female and young bears in BVCs. Young bears and females with dependent offspring often select areas close to human settlements to avoid infanticide by males (Steyaert et al. 2013; Elfström et al. 2014). This type of mortality is critical for local population demography and overall conservation efforts (Palomero et al. 2007). Location H4, at which 50% (eight out of 16) of the involved bears were of young age, plays a major role in conservation efforts. Furthermore, the number of males denotes dispersal behavior, as dispersal in bears is sex-biased (Zedrosser et al. 2007) and location H4 is considered to be the main corridor connecting the Vernon and Voras mountains; with the former hosting part of the source population and the latter being an area of population recovery during the past decades. Wildlife-vehicle collisions are common in H4 as the landscape topography funnels wildlife there. However, BVCs eliminate would-be-crossers, reduce abundance and connectivity (Jackson and Fahrig 2011) and hence, they jeopardize the successful recovery of the species in Voras and the adjacent mountains (e.g., Pinovo and Tzena).

Wildlife-vehicle collision prevention measures include fencing combined with crossing opportunities, animal detection systems and seasonal wildlife warning signs (Huijser et al. 2009; Huijser and McGowen 2010). In Greece, a bear-proof fence (2.2 m high, 0.8 m overhang with a negative angle, 1.5 m horizontal mesh), has been installed on both sides of motorway A29 and along the south-western segment of A2.

This fence in combination with the retention of safe passages for the animals (e.g., overpasses and underpasses) has substantially decreased BVCs in location H2. Specifically, approximately 20 BVCs occurred on motorway A29 from its operation (2009) until the complete fence installation in 2014; since then, only one BVC occurred on the motorway (2015). Similarly, the motorway in location H3 has also been fenced and not a single BVC has been recorded since then. Yet, collision hotspots do not always indicate the optimal location to install mitigation measures (Zimmermann-Teixeira et al. 2017), and while placement of mitigation measures is vital in predicting effectiveness, preserving road permeability and habitat connectivity are also important aspects for planners to consider (Glista et al. 2009); especially since locations with high wildlife crossing rates do not always overlap with collision hotspots (Find'o et al. 2019).

Fencing is an effective mitigation measure in decreasing wildlife-vehicle collisions that when implemented appropriately can eliminate barrier effects and collision clustering at fence ends (Clevenger et al. 2001; Huijser and McGowen 2010). However, for areas like locations H1 and H4, fencing does not seem to be the best choice. Location H4 lacks the wildlife safe passage opportunities, and a fence would create an unsurpassable obstacle, which would hinder animal movement in the corridor connecting the Vernon and Voras mountains. Other collision countermeasures, such as animal detection and animal warning systems should be evaluated and considered in location H4 to minimize collisions. Location H1 poses an even greater challenge though. As BVCs occur on several roads in this peri-urban landscape, fencing is not a realistic option, whereas animal warning systems may only transfer the problem from one road to another. Adoption of animal detection systems, driver warning signs and speed reduction measures can contribute to decreasing BVCs in the area. Still, local driver awareness raising will be key in encouraging and ensuring slower and more careful driving in the area, and ultimately achieving the reduction of wildlife vehicle collisions.

Wildlife-vehicle collisions are the product of various factors such as road surface and environmental characteristics, as well as, road traffic, wildlife abundance and driving conditions (Seiler 2005; Neumann et al. 2012). In the present study, we found that most BVCs occur in hotspot locations when bear mobility increases and other BVC-favorable conditions are met, i.e. poor light conditions and low visibility. Wildlife-vehicle collision prevention solutions are necessary to minimize BVCs and enhance road safety for both wildlife and humans.

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