



Characterization of recent wild pig-vehicle collisions in Georgia, USA

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Abstract

Vehicle collisions with wild pigs (*Sus scrofa*) are reported almost everywhere this species is found. However, this is one of the least studied and characterized forms of damage that these invasive animals cause in the United States (U.S.). We analyzed 518 wild pig-vehicle collisions (WPVCs) that took place statewide in Georgia between 2015 and 2021. From that dataset, we analyzed several parameters in order to better understand and characterize these accidents on a scale that had previously not been done in the U.S. Wild pig-vehicle collisions were reported from 105 out of the 159 counties in Georgia, increasing in number annually over the seven-year period. WPVCs were most likely to occur in the fall (37%). A duration weighted time of day analysis showed that WPVCs were most frequent at dusk. Most (97%) reported accidents were caused by live wild pigs, with the remainder being due to collisions with already dead or road-killed pigs. Most (86%) collisions involved a single wild pig while the remainder occurred with two or more pigs. Collisions occurred mostly with passenger cars on dry, straight, and level two-lane blacktop roads under dark, unlighted conditions. Nine percent of the vehicle accidents involving wild pigs resulted in injuries to the drivers and passengers. Some of the most severe injuries reported were caused by swerving to avoid striking wild pigs. No human fatalities were recorded due to these accidents. Wild pig-vehicle collisions are costly and dangerous and should be closely monitored and mitigated by the agencies responsible for motorist safety, transportation infrastructure, and wildlife management.

Keywords Georgia · Human safety · Injury · *Sus scrofa* · Vehicle collision · Wild pig

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Introduction

As road infrastructures expanded and wild animal densities increased, wildlife-vehicle collisions (WVCs) in the United States (U.S.) have escalated from 1974 through the present (Puglisi et al. 1974; Reilly and Green 1974; Huijser et al. 2008; Abraham and Mumma 2021). Between one and two million WVCs with large animals have been reported to occur annually in the U.S. (Huijser et al. 2008), with such accidents costing U.S. drivers approximately \$8,388,000,000 annually (Huijser et al. 2008). In addition, an estimated 58,622 humans are injured and about 440 more are killed every year in WVCs (Conover 2019).

Introduced wild pigs (*Sus scrofa*) are one of Georgia's largest-bodied and abundant terrestrial wildlife species (Golley 1962; Kammermeyer et al. 2003). As a highly mobile species (Mayer and Brisbin 2009, Saxena et al. 2020; Brieger et al. 2022) with their large body mass,¹ low center

¹ Mayer and Brisbin (2009) reported that the average adult body mass of wild pigs in the U.S. is approximately 85 kg; Kammermeyer et al. (2003) reported that very large wild pigs in Georgia can exceed

of gravity (Mayer and Johns 2007), and gregarious social behavior (Mayer and Brisbin 2009, Sáenz-de-Santa-María and Tellería 2015, Saxena et al. 2020; Brieger et al. 2022), wild pigs represent an increased human safety and economic risk with respect to collisions with vehicles.

In contrast to such accidents in Europe (e.g., Primi et al. 2010; Thurfjell et al. 2015; Kruuse et al. 2016; Jägerbrand and Gren 2018), wild pig-vehicle collisions (WPVCs) in the U.S. have historically been both little studied by researchers and underreported by government agencies. However, WPVCs in the U.S. have recently been identified as a growing risk to property and human safety (Mayer and Johns 2007; Beasley et al. 2013; Mayer et al. 2021). Potential damage from WPVCs in the U.S. was recently estimated to be greater than \$181 million per year (Strickland et al. 2020). As with WVCs, WPVCs have also caused injuries and fatalities in the U.S. for the drivers and passengers involved (e.g., Associated Press 2017, Hyde 2021; Jasper 2021; Willetts 2021).

To date, all studies characterizing WPVCs in the U.S. have focused on only two localized federal properties (i.e., Mayer and Johns 2007; Rosenfeld et al. 2002, 2009; Beasley et al. 2013; Mayer et al. 2021; Pakula et al. 2023). Although populations of introduced wild pigs are widespread throughout the southern and western U.S., data associated with WPVCs have not been reported on a statewide scale anywhere in this country. Since wild pigs occupy a wide variety of landscapes, time zones and climatic regions across the U.S. (Mayer and Brisbin 2009), the very localized data reported in these earlier studies may not be representative of the characteristics of WPVCs over larger scales. Other aspects of WPVCs that are underrepresented in the literature are the proportion of live versus dead (already road-killed) animals resulting in collisions, roadway composition and configuration at the accident scene, road lighting characteristics, surface condition of road, and the proportion of accidents caused by swerving to avoid striking wild pigs.

Our objective was to analyze and characterize WPVCs in the State of Georgia, USA, and to provide data from a larger geographic area than has yet been studied in this country. These study results could assist wildlife and transportation managers in mitigating the frequency and severity of these accidents. Based on previously published general information on both WVCs and WPVCs (e.g., Mayer and Johns 2007; Huijser et al. 2008; Rodríguez-Morales et al. 2013; Sáenz-de-Santa-María and Tellería 2015), we predicted in this study that WPVCs in Georgia would occur in counties across the state where wild pigs are reported to

be present, occur at night in the summer or fall months, be caused mostly by single, live pigs, occur more frequently on straight two-lane roadways with dry surfaces, and result in a small number of human injuries (~3–6% of the accidents).

Materials and methods

Study area

Georgia is located in the southeastern U.S. along the Atlantic coast and is the largest U.S. state by total land area east of the Mississippi River, encompassing 149,976 km² (USCB 2022). Georgia contains six distinct ecoregions, with the topography rising from sea-level at the edge of the Southern Coastal Plains through the Southeastern Plains, Piedmont, Blue Ridge, Ridge and Valley, and Southwestern Appalachians ecoregions, topping out at 1,433 m elevation (Griffith et al. 2001). The climate is humid subtropical, with a mean annual temperature of 17° C and a mean annual rainfall of 126.3 cm (U.S. Climate Data 2022). Georgia's transportation infrastructure includes 204,165 km of variously sized roadways including interstate highways, county roads, urban/city roads, and small rural roads (Wiegand 2021).

Introduced wild pigs have been present in Georgia since the 1500 s, and until the 1980s, wild pigs were found only in the Southern Coastal Plains, Southern Plains, and a few counties in the Blue Ridge ecoregion of the state (Hanson and Karstad 1959; Golley 1962; Mayer and Brisbin 2008). Over the past three decades wild pigs have substantially increased both their distribution and population size across the U.S. (VerCauteren et al. 2020). Concurrent with that national expansion, wild pigs in Georgia have increased their range and numbers throughout all six ecoregions in the state (Figs. S1A, S1B). In 2021, wild pigs were reported throughout the state except for the Atlanta metropolitan area (USDA 2023).

Data analysis

The Georgia Department of Transportation (GDOT) maintains a database of traffic accidents documented by state, county, and local police departments (<http://www.dot.ga.gov/DS/Crash>). On 20 April 2022, we requested GDOT to perform a custom data query to extract all animal crashes from 2015 (i.e., the earliest digitized records available) through 2021 from the database. The dataset GDOT provided contained 117,791 records of 45 variables (Table S1). We reviewed each record, confirmed that the accident was caused by animals (wildlife or domesticated), and assigned a species to each record, when possible, by using the string variable “NarrativeTxt” containing the narrative of the accidents and the two categorical “event”

Footnote 1 (continued)

227 kg in weight; Georgia Game and Fish (1967) reported the harvest of a 245-kg wild pig by a hunter in Burke County, Georgia.

variables “U1FirstHarmfulEvent” and “U2FirstHarmfulEvent” describing the first and second causes of the accident (with possible responses including “deer” or “animal”). To assign a record to the species “wild pig”, we followed the subsequent procedure. First, we used an automated process to tag the records as “pig” if the “NarrativeTxt” column included one of the four search terms “hog”, “pig”, “swine”, or “boar”, then manually excluded records that included the search terms but were unrelated to WPVCs. Examples of these include accidents that occurred on Hog Mountain Road, near Zombie Pig BBQ, and one accident that happened due to the driver eating pig skins at the time of the accident. After reducing the collisions to only those caused by collisions with pigs or by the driver attempting to evade a pig, we removed records involving domestic swine (e.g., pot-bellied pig, pet pig, pig taken to animal hospital after collision, etc.). We then considered all remaining records of collisions to have involved wild pigs. Lastly, for wild pig records that were missing GPS coordinates, when possible, we generated the spatial location based on the columns “Route”, “IntersectingRoute”, and “DistanceFrom” in the collision record.

We started by providing the count of WPVC by year and by county. We then compared the counties where WPVCs occurred to the Georgia counties where wild pigs were reported to be present based on the National Feral Swine Mapping System (NFSMS) produced by the U.S. Department of Agriculture. The 2015 county map was provided by SCWDS (2015). The 2016 through 2021 maps are available at USDA (2023).

To assess the distribution of WPVCs in time, we generated a “Season” variable with observations categorized as “Winter” (December to February), “Spring” (March to May), “Summer” (June to August), or “Fall” (September to November). For each observation where GPS coordinates were available or derived, we also calculated the time of “sunrise”, “sunset”, “night” (i.e., beginning of night), and “end of night” for the day of the crash based on its latitude and longitude using the RDocumentation function “getSunlightTimes” from the package *suncalc* (RDocumentation 2022). We created a “Time of day” categorical variable with records categorized as “Day” if the crash took place between sunrise (top edge of the sun appears on the horizon) and sunset (sun disappears below the horizon), “Dusk” between sunset and beginning of night (dark enough for astronomical observations), “Night” between beginning of night and end of night (morning astronomical twilight starts), and “Dawn” between end of night and sunrise. Each “Time of day” period has a different duration. If we found that WPVCs were distributed equally among each of the time periods, (25% of collisions occurring during day, dusk, night, and dawn), we would infer that WPVCs are more common

at dusk than during the day because the day has a longer duration than dusk. To account for the different durations, τ , of each of the time periods from each other and over the course of the year, we created a period duration weight w (proxy to the likelihood of a crash per hour) calculated as:

$$w = 1/\tau$$

We generated distributions of the number of collisions by season and both unweighted and weighted distributions by time of day for wild pigs. We performed Chi-squared tests to determine if the wild pig distributions were uniformly distributed by season and by time of day using the function “chisq.test” from the package *stats* (Bolar et al. 2019; version 4.1.2) and “wtd.chi.sq” from the package *weights* (Pasek et al. 2016; version 1.0.4). Because vehicle collision occurrences tend to cluster in the same locations, creating positive spatial autocorrelation, neighboring observations may not be fully independent of each other (Matkan et al. 2013). One way to address the issue is to adjust the Type I error rate α to a more conservative but arbitrarily chosen value: e.g., $\alpha/5$. (Dale and Fortin 2002). Additionally, if multiple hypotheses are tested, the probability of observing a rare event increases, and therefore, the likelihood of incorrectly rejecting a null hypothesis (i.e., making a Type I error) increases. To compensate for that increase, we used the Bonferroni correction by testing each individual hypothesis at a significance level of α/m , where α is the desired overall significance level and m is the number of hypotheses (Weinstein 2004). For example, the number of pairwise comparisons when testing for seasonality would be $m = 4 * 3/2 = 6$. Finally, we reported distribution summary statistics for the characteristics of the pigs involved (i.e., number of pigs, live versus already dead), vehicle type, and the type of collision (i.e., direct hit versus swerved to avoid collision). Where available in the narrative, any anecdotal descriptions of the size and coat coloration of the pigs involved in the collisions were also compiled. Size was included since it relates to safety risk in these accidents (Mayer et al. 2021). Darkly colored pigs would likely be harder to see in low light conditions (Pakula et al. 2023). Given the diversity of sources for these accident reports, we were unable to obtain complete sets of information (e.g., size and coat coloration) on a number of these accidents, but we recorded all available information possible. Distribution statistics were also calculated for the following string variables from the database: “Surface”, “MnvrVeh1”, “RoadComposition”, “U1NumberOfLanes”, “U1TrafficWayFlow”, “Light”, “CrashSeverity”, and “Injuries”. The column with the “Surface” variables refers to whether the road was wet or dry. The “MnvrVeh1” variable included variables such as “straight”, “negotiating a curve”, or “turning”. The “RoadComposition” variable included the road surface types—“black top”, “concrete”,

Table 1 Listing of the number and percentage of animal-vehicle collisions in Georgia, 2015–2021

Species/Taxon	Scientific Name or Taxon	Vehicle collisions	
		Number	Percentage
White-tailed Deer	<i>Odocoileus virginianus</i>	99,316	88.3
Domestic Dogs and Cats	<i>Canis familiaris</i> and <i>Felis catus</i>	4,950	4.4
Unknown Animal	Kingdom Animalia	4,339	3.9
Livestock (misc.)	Clade Ungulata	1,642	1.5
Mesocarnivores	Order Carnivora	821	0.7
Birds	Class Aves	573	0.5
Wild Pigs	<i>Sus scrofa</i>	535	0.5
Black Bear	<i>Ursus americana</i>	294	0.3
Total		112,470	100.0

“dirt”, or “tar and gravel”. The “NumberOfLanes” column listed the total number of lanes on the roadways where the WPVC occurred. “UITrafficWayFlow” describes whether a physical separation between lanes was present. The variable “Light” referred to the light conditions based on period of day (e.g., dusk, daylight, dark, etc.). The “CrashSeverity” column describes the seriousness of the injuries sustained during the collision. The scoring was based on the descriptions in Table S2. The “Injuries” column lists the number of injuries sustained by drivers and passengers in the collision. The injury data were also compared to the type of vehicle.

To explore the relationships between collisions by traffic way flows and number of lanes, we removed observations for which the variable “traffic way flow” was missing and for which the variable “number of lanes” was equal to zero or greater than 16. Traffic way flow refers to the separation between lanes (e.g., roads can be two-way with no separation, or one set of lanes can be separated from the other by a median or a physical barrier). To compare the distribution of collisions by number of lanes with the proportion of roadways having the same characteristics, we calculated the number of kilometers of the road type in Georgia by number of lanes using ArcGIS.

All of the variables used in this study are listed in Table S3. This list includes the names, descriptions and examples of the different variables.

Results

Of the 117,791 accident records provided by Georgia DOT, 113,740 occurred over the seven-year study period, of which we were able to assign 112,055 to at least one animal [including black bear (*Ursus americana*), white-tailed deer (*Odocoileus virginianus*), domestic dog (*Canis familiaris*), cat (*Felis catus*), wild pig, or other animal species]. Only about 0.5% of these accidents ($n = 518$ accidents) were caused by wild pigs (Table 1).

Reports of WPVCs occurred in 105 of the 159 counties in Georgia during the study period (Fig. 1). Dougherty County had the most with 26 (5%); followed by Houston (23; 4.4%), then Liberty, Montgomery, and Wilkinson with 18 each (3.1%). Annually, the number of counties reporting WPVCs increased from 33 in 2015 to 44 in 2021. This overall increasing trend was concurrent with the increasing number of Georgia counties reporting the presence of wild pigs (Fig. 2). However, WPVCs were recorded in several counties during years when wild pigs were not reported on the NFSMS maps as being present. Specifically, these inconsistencies were as follows: 2016 – Lamar County (1 WPVC), Rockdale County (1 WPVC); 2017 – Troup County (1 WPVC); 2018—DeKalb County (2 WPVCs), Hall County (3 WPVCs), Lamar County (2 WPVCs), Troup County (1 WPVC); and 2019—DeKalb County (1 WPVC).

The number of WPVCs increased during the survey period from 57 in 2015 to 79 in 2021, with a peak in 2018 of 103 WPVCs (Fig. 2).

WPVCs varied seasonally ($\chi^2 = 47.714$, $df = 3$, $p < 0.001$; Fig. 3), with most occurring in the fall (37.3%), followed by spring (24.9%), summer (20.7%), and winter (17.2%). Pairwise comparisons with Bonferroni correction showed that the likelihood of a WPVC to occur in the fall was greater than in any other season, but there were no other significant differences between seasons except between spring and winter.

We analyzed the effect of time of day (Fig. 4) on only those 500 WPVCs that had GPS coordinates (i.e., needed to calculate time of day parameters with the `suncalc` package; RDocumentation 2022). Time of day had a significant influence on WPVCs ($\chi^2 = 234.93$, $df = 3$, $p\text{-value} < 2.2e\text{-}16$). None of the pairwise comparisons with Bonferroni correction resulted in a statistically significant difference between periods except those involving night: the portion of WPVCs occurring at night (55%) was significantly greater than during dawn (14%), day (14%) and dusk (17%). When weighting each observation to account for the duration of the period it occurred in (Fig. 5), we found a statistically significant

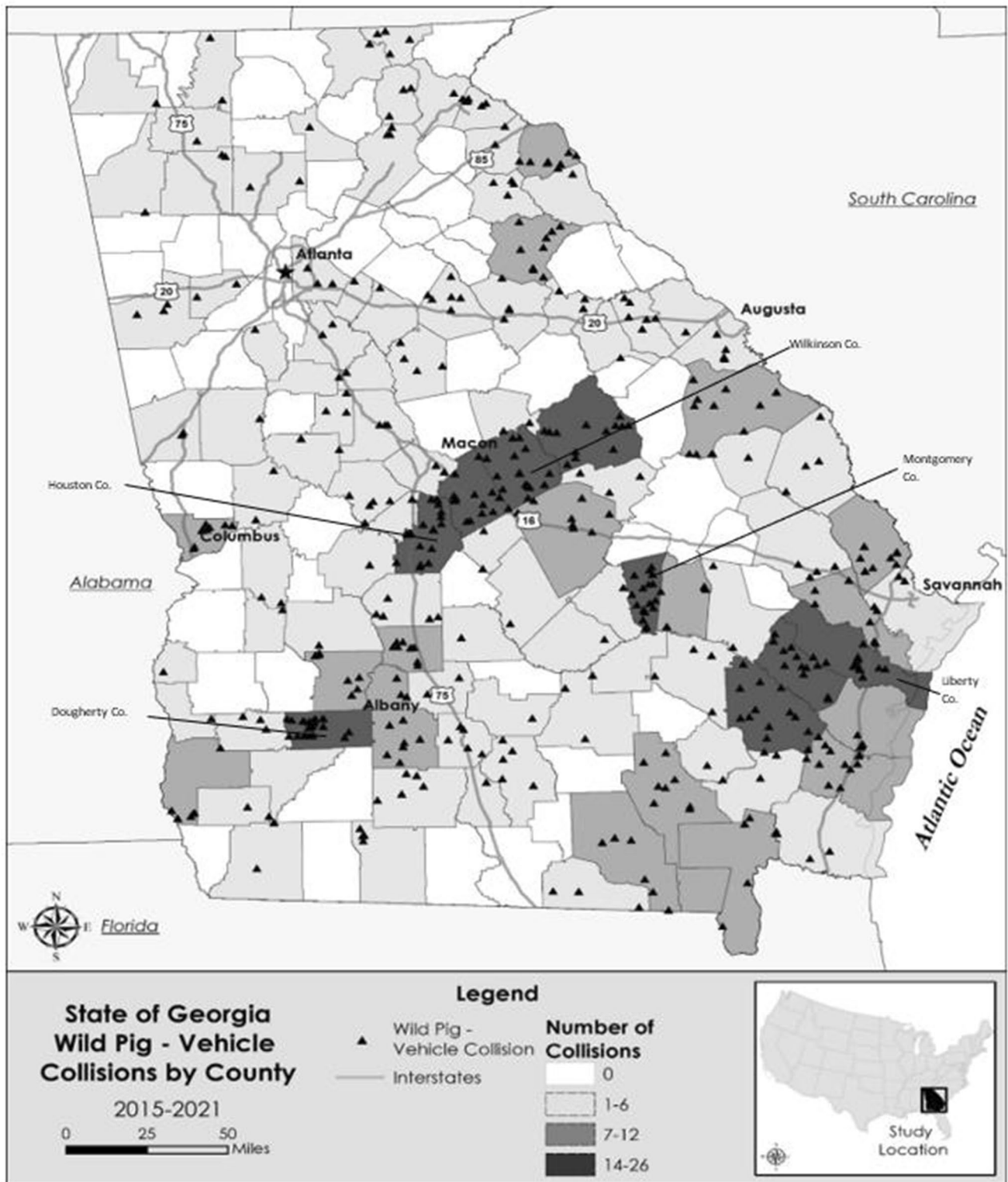


Fig. 1 Locations of wild pig-vehicle collisions in Georgia, USA, by precise location (triangles) and aggregated by county (polygons), 2015–2021

difference between time periods ($\chi^2 = 744.98$, $df = 3$, $p\text{-value} < 2.2e-16$). Pairwise comparisons with Bonferroni correction showed a statistically significant difference

between each pair of periods except between dawn and dusk. The weighted share of WPVCs was greater for dusk (40.8%), followed by dawn (33.9%), night (21.2%), and day (4.1%).

Fig. 2 Comparison of the annual number of Georgia counties where wild pigs were reported (black bars) and the annual number of wild pig-vehicle collisions (WPVCS) in Georgia (white bars) from 2015 through 2021. The black line is the trend line for the annual number of Georgia counties reporting wild pigs and the dashed line is the trend line for the annual number of WPVCS

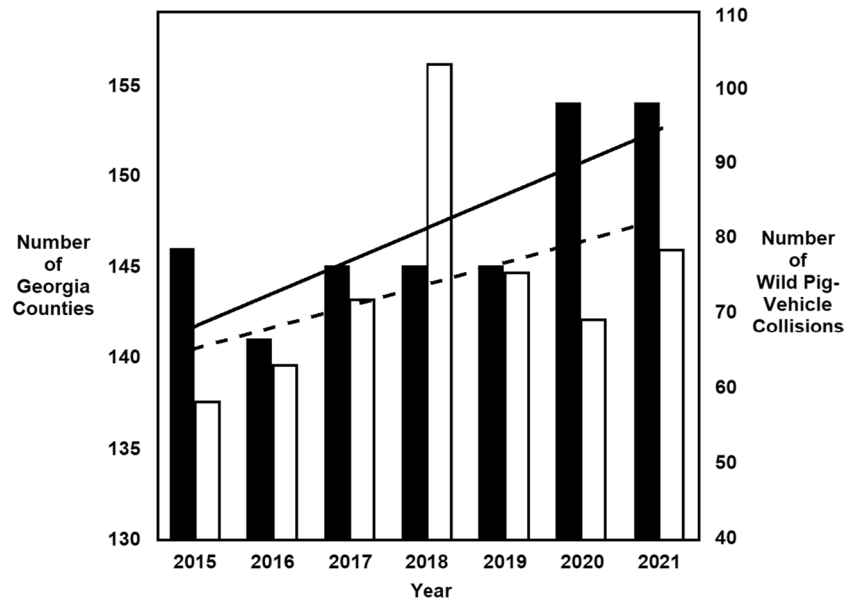
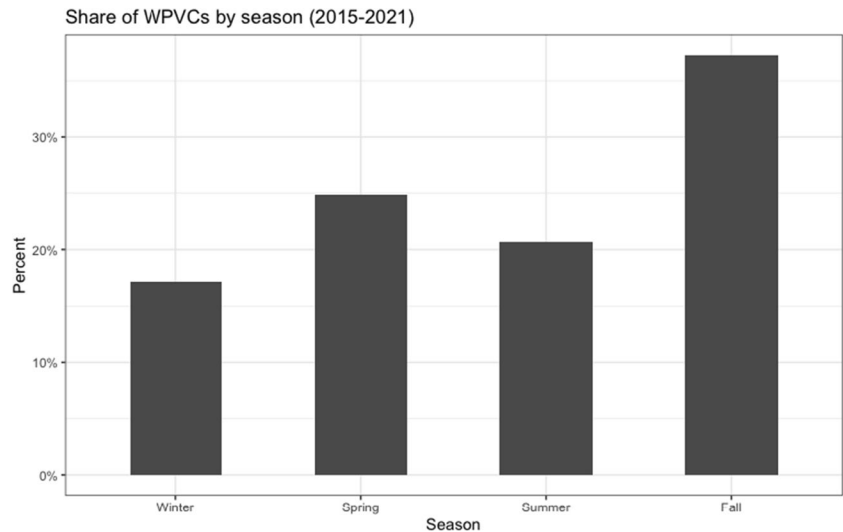


Fig. 3 Wild pig-vehicle collisions by season in Georgia, USA, 2015–2021



Five hundred WPVCS (96.5%) were caused by live wild pigs, and 18 (3.4%) were the result of wild pigs that were already deceased (i.e., road-killed) and lying in the roadway or on the shoulder of the road. Of the 518 records in the WPVC dataset, 443 collisions (85.5%) occurred with single wild pigs, and the remaining 75 (14.5%) involved two or more wild pigs. The number of multiple pigs hit averaged 2.9 (range = 2–7). Subjective numbers of reported multiple pigs hit included “several” ($n = 8$), “group” or “multiple” (each at $n = 2$), and “bunch”, “herd”, “numerous”, and “passel” (all at $n = 1$). In 22 of the collisions, only one out of a reported group of two or more wild pigs in the narrative was hit in the accident. The largest group of wild pigs observed crossing a road was reported in the accident narrative as “20–25”. Of the 26 wild pigs

that had a coat coloration described in the narrative, most (76.9%) were black, followed by brown (15.4%), “dark colored” (3.8%), and white (3.8%). Size descriptions for 37 pigs included large, big and very large (collectively at 75.7%) and small (24.3%).

Most vehicles involved in WPVCS were passenger cars (57.7%), followed by sport utility vehicles (18.1%) and pickup trucks (14.5%). The remaining collisions occurred with vans (3.9%) and tractor/trailers (1.4%) with all other vehicle types comprising 2.5% of the collisions.

Direct hits occurred in 493 of the collisions (95.1%), whereas 23 (4.4%) were near misses caused by swerving to avoid a collision. One collision event involved the first vehicle swerving to avoid a direct hit and a second vehicle making a direct hit. And finally, one record did not indicate

Fig. 4 Wild pig-vehicle collisions by time of day in Georgia, USA, 2015–2021

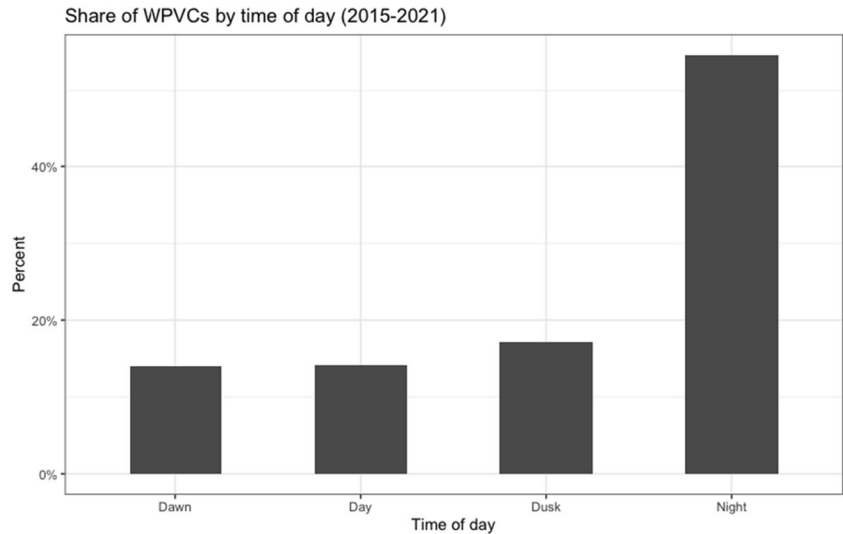
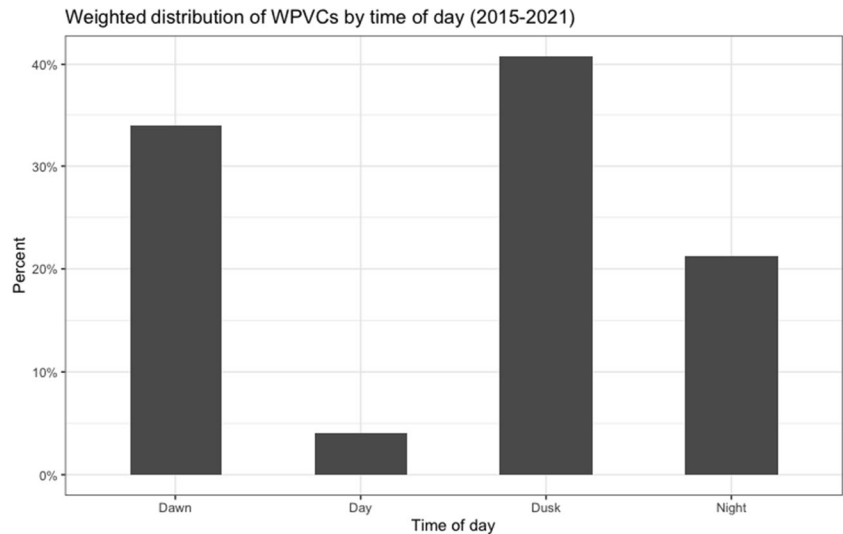


Fig. 5 Wild pig-vehicle collisions per hour by time of day in Georgia, USA, 2015–2021



whether the collision was caused by a direct hit or by an avoidance maneuver.

Most WPVCs occurred on blacktop roads (90.7%). Very few WPVCs were recorded from concrete surfaces (5.4%), and the remaining 4% were on either dirt, tar and gravel, or an unreported surface type. Most collisions occurred while a vehicle was traveling straight (91.3%) on a straight and level road (77.9%). Eight percent of collisions occurred while negotiating a curve (both level and on a grade) and 13.7% occurred on a grade (either traveling straight or turning). Only 2.9% of WPVCs occurred on the crest of a hill, and there were only two recorded collisions that occurred while turning. Most WPVCs occurred outside of an intersection (77%) while 16.8% happened within an intersection. The remaining collisions (6.2%) occurred on the shoulder, off the roadway, in the median, or at the intersection with a driveway. The road was dry

in 85.1% and wet in 13.7% of reported WPVCs. One collision record reported standing or moving water, and five records were reported as “invalid” for the surface variable. Most WPVCs (74.1%) occurred after dark on roads that were not artificially lighted. Based on the data collected by GDOT, a total of 14.9% of WPVCs were reported as happening during daylight hours, while 10.4% occurred at dawn, dusk, or dark with artificial light. Three collision records did not indicate artificial light condition at the time of the accident.

The majority (80.4%; Fig. 6) of WPVCs occurred on two-way traffic ways with no physical separations. Most WPVCs (84.4%) occurred on 2-lane roadways while 12.2% took place on roadways with 4 or more lanes (Fig. 7). The most common corresponding roadways in Georgia were 2 lanes (93.5%) with far fewer kilometers among roadways > 4 lanes (5.3%), 1 lane (0.7%) or 3 lanes (0.5%).

Fig. 6 Wild pig-vehicle collisions by traffic way flow in Georgia, USA, 2015–2021

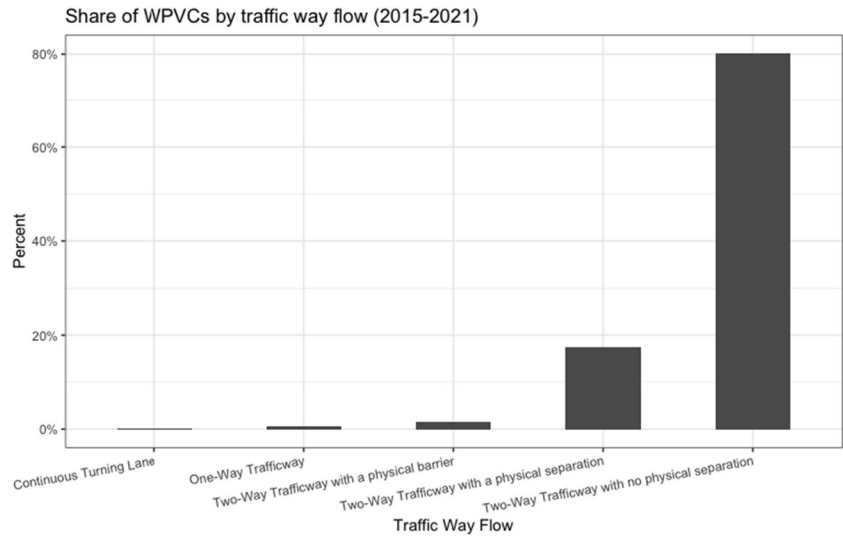
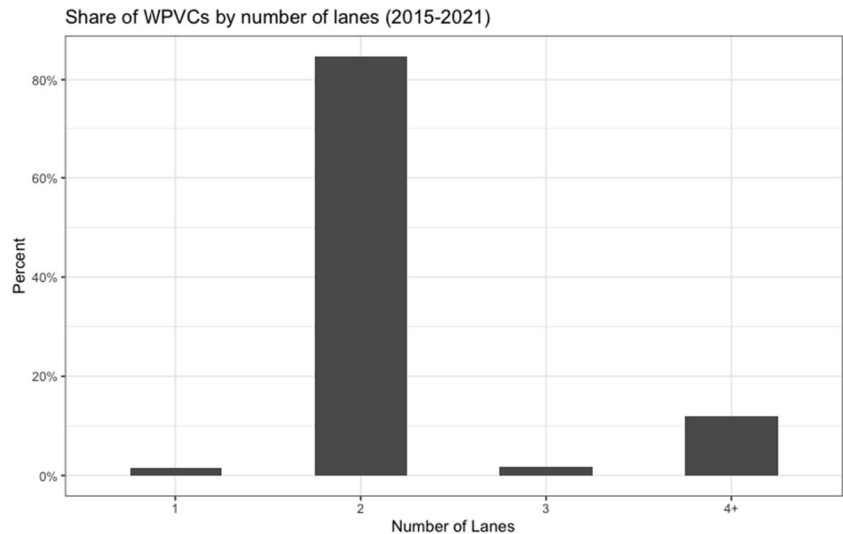


Fig. 7 Wild pig-vehicle collisions by number of lanes in Georgia, USA, 2015–2021



Among the 518 WPVC events, 47 collisions (9.0%) resulted in 58 reported injuries. Of these injuries, five (8.6%) were classified as “serious”, 20 (34.4%) as “visible” and 33 (56.8%) as “complaint”. No human fatalities were reported to have resulted from these accidents. Some wild pig-initiated accidents, both direct hits and near misses, cascaded into collisions with other vehicles (16, 3%) or other objects (1.9%; e.g., trees, guard rails, fences, poles, etc.). Five rollovers (0.9%) and four ditch incursions (0.7%) also resulted from collisions with wild pigs.

Of the eight types of vehicles included in the WPVCs, only all-terrain vehicles (ATVs), motorcycles, passenger cars, pickup trucks, and sport utility vehicles (SUVs) were involved in accidents where injuries to the human occupants were reported (Table 2). No injuries were reported to have occurred in WPVCs involving larger vehicles (i.e., including ambulances, single unit trucks, and tractor/trailers).

Discussion

Most reported WVCs in the U.S. (as high as 90%) involve deer in the genus *Odocoileus* (Huijser et al. 2008). Similarly, most WVCs reported in Georgia in 2015–2021 involved white-tailed deer, with WPVCs being only a fraction of the total number of WVCs in that state (Table 1). This is in contrast to portions of the native species range where WPVCs are the most numerous type of WVC (e.g., Spain: 50.6%—Rodríguez-Morales et al. 2013; Belgium: 61%—Morelle et al. 2013). However, based on these numbers from Georgia, white-tailed deer would represent a significantly greater safety risk than wild pigs with respect to vehicle collisions. If widespread, this lower frequency of WPVCs may be the reason for the general lack of studies characterizing these accidents in the U.S.

Table 2 Number of each type of vehicle involved in the WPVCs in Georgia and the class of injuries sustained by the vehicles' occupants

Type of vehicle	Number of collisions	Reported class of injuries			
		No apparent injury	Possible injury of complaint	Suspected minor or visible injury	Suspected serious injury
		Number	Number	Number	Number
All-Terrain Vehicle	1 (0.20)	–	–	1 (7.14)	–
Ambulance	1 (0.20)	1 (0.22)	–	–	–
Motorcycle	1 (0.20)	–	–	–	1 (33.33)
Passenger Car	299 (59.56)	273 (60.53)	21 (61.76)	4 (28.57)	1 (33.33)
Pickup Truck	75 (14.94)	69 (15.30)	3 (8.82)	3 (21.43)	–
Single-Unit Truck	4 (0.80)	4 (0.89)	–	–	–
Sport Utility Vehicle (SUV)	94 (18.73)	77 (17.07)	10 (29.41)	6 (42.86)	1 (33.33)
Tractor/Trailer	7 (1.39)	7 (1.55)	–	–	–
Van	20 (3.98)	20 (4.43)	–	–	–

Percentages shown in parentheses

In general, the number of WPVCs in an area is reported to be positively correlated to the local wild pig population size (Okarma et al. 1995; Groot Bruinderink and Hazebroek 1996; Balčiauskas 2009). The concentrated locations of WPVCs in the Southern Coastal Plains and Southeastern Plains ecoregions in Georgia (Fig. 1) are consistent with the range of the historically oldest, largest, and most widespread populations of wild pigs in that state (Hanson and Karstad 1959; Golley 1962; Mayer and Brisbin 2008; Corn and Jordan 2017). The occurrence of WPVCs in counties where wild pigs were not reported to be present, all of which were in the Piedmont ecoregion, is likely due to a couple of factors. First, low and infrequent (year to year) numbers of WPVCs in a county is likely consistent with a low population size or density. Corn and Jordan (2017) defined the NFSMS maps as depicting established populations of wild pigs, defined as populations where wild pigs have been present for > 2 years and there is evidence of reproduction. Based on the year-to-year changes in these maps, the five counties with WPVCs that were not included on the NFSMS maps as having wild pigs present were likely newly established, localized, and low-density populations. Second, the 2022 update of the NFSMS county map for Georgia indicates wild pigs are now present in every county in the state (USDA 2023) (i.e., populations in counties not previously shown as occupied were in the process of establishment at the time of those accidents).

The decrease in WPVCs in 2020 was likely due to an unprecedented reduction in traffic volumes in Georgia, as has been the case for many U.S. roads and highways during the COVID-19 pandemic (Shilling et al. 2021). This decrease would appear to support the hypothesis that the risk and rates of WVCs are tied to traffic volumes (e.g., Litvaitis and Tash 2008). In 2021, reports of WPVCs increased

by 14% over the previous year, concurrent with a post-pandemic increase in traffic volume. Over the seven-year period of this study, 2018 was the peak year for WPVCs (103), which was also the tenth wettest year on record for Georgia (NOAA 2022) with Atlanta receiving 49.8 cm more rain than the 30-year average (NWS 2022). In an eight-year study of wild boar in the Mediterranean, the percentage of pregnant sows was higher and litter size increased during greater rainfall years (Fernández-Llario and Mateos-Quesada 2005). Assuming the same response in wild pigs in the southeast U.S., we would expect an increase in young and naïve wild pigs on the landscape. In addition, higher than average rainfall potentially pushed wild pigs out of low-lying, inundated areas, triggering greater movement and increasing the chance of vehicle collisions (Frädrich 1974, Mayer and Brisbin 2009).

WVCs are reportedly highly seasonal due to annual movement patterns (e.g., seasonal foraging), breeding cycles, and disturbance during the hunting season (Huisjer et al. 2008; Diaz-Varela et al. 2011; Putzu et al. 2014; Thurfjell et al. 2015; Stickles et al. 2015). Within the native range of Eurasia and North Africa, the peak seasonal occurrence of WPVCs is consistently during breeding and hunting season in the fall and winter months (Groot Bruinderink and Hazebroek 1996; Gethöffer et al. 2007; Peris et al. 2005; Primi et al. 2010; Diaz-Varela et al. 2011; Lagos et al. 2012; Rodríguez-Morales et al. 2013; Putzu et al. 2014; Thurfjell et al. 2015; Kruuse et al. 2016, Kučas and Balčiauskas 2020). We found a similar increase in Georgia WPVCs occurring in the fall. In contrast, Mayer and Johns (2007) reported a statistically significant monthly peak in August with a smaller peak in December in WPVCs in South Carolina. Further, Rosenfeld et al. (2002, 2009) reported a seasonal peak for WPVCs in Florida in the spring, with a

smaller peak in the fall. Although wild pigs in the introduced range breed sporadically year-round, in contrast to strongly seasonal breeding in Europe, the peaks reported by Mayer and Johns (2007) are consistent with the start of the peak breeding season in August and the start of a smaller annual breeding peak in December (Mayer and Brisbin 2009). In the peaks in Florida, the WPVCs coincided with increased movement associated with foraging in citrus groves in the spring and mast-producing hammocks in the fall (Rosenfeld et al. 2002, 2009).

Introduced wild pigs in the U.S. have a low physical profile and most (91%) are darkly or cryptically (e.g., spotted coat pattern) colored animals (Mayer and Brisbin 2008, 2009). Although a small sample size in the GDOT database narrative, most of the pigs were described as being darkly colored. Given that most (86%) WPVCs in our study occurred during low or limited light conditions (i.e., night, dawn, and dusk), it is possible that the driver was not able to clearly see the pig in time to brake or avoid a collision with the animal despite driving on a straight roadway. Pakula et al. (2023) reported that the detection distances for wild pigs by drivers at night were approximately 50% of that for white-tailed deer. Those authors suspected that collectively the lack of eyeshine, short stature, and dark pelage color likely influenced the ability of drivers to detect these pigs sooner. Pakula et al. (2023) considered nighttime encounters with wild pigs 100% dangerous due to the inability of drivers to detect pigs with enough time to brake to avoid a collision.

Throughout wild pigs' global range, WPVCs typically occur during nighttime hours (Groot Bruinderink and Hazebroek 1996; Rosenfeld et al. 2002; Mayer and Johns 2007; Primi et al. 2010; Diaz-Varela et al. 2011; Rodríguez-Morales et al. 2013; Putzu et al. 2014; Kruuse et al. 2016), with increased occurrences around dawn and dusk also being reported (Kušta et al. 2017, Kučas and Balčiauskas 2020). This study corroborates these previous findings. Visibility is limited for both drivers and pigs at dawn, dusk, and night, and this, combined with their mostly dark coat coloration, increases the likelihood of collisions (Huijser et al. 2008; Rodríguez-Morales et al. 2013; Pakula et al. 2023).

Daily activity patterns of wild pigs vary by location. Where they are relatively undisturbed, wild pigs trend toward diurnal activity (Gundlach 1968; Frädrieh 1974). In contrast, areas with intense hunting pressure or human activity during the day will drive pigs to become more nocturnal (Waithman 2001, Mayer and Brisbin 2009). In Georgia, wild pigs can be legally hunted throughout the year (Kammermeyer et al. 2003) with an average of 98,300 pigs being recently harvested statewide by hunters annually (C. Killmaster, Georgia Department of Natural Resources, personal communication, 6 July 2022). As early as the 1950s, Hanson and Karstad (1959) reported that some wild pig populations in Georgia had already become largely nocturnal in their

behavior due to increased hunting pressure. More recently, these largely nocturnal activity patterns have continued to be exhibited by Georgia's wild pigs (Hanson 2006; Pinkston 2008). Such nocturnal activity is consistent with the timing of WPVCs we observed.

Two or more individual pigs were struck in 14% of the WPVCs reported during the study period. Wild pigs are social animals frequently found in groups composed of two or more individuals. These groups, called sounders, typically consist of one or more sexually mature females and their collective generations of young (Frädrieh 1974, Mayer and Brisbin 2009). Typically, wild pigs cross roadways in groups (Saxena et al. 2020; Brieger et al. 2022). Sounders of wild pigs can cause serious accidents when multiple individuals are struck during a single collision, and multiple vehicles can collide with different members of a sounder. For example, one WPVC reported from Central Europe was comprised of 23 wild pigs (Vilíková 2010).

Road-killed wild pigs also cause vehicle collisions, either through direct hits or near misses (Mayer and Johns 2007). During our study, one road-killed pig resulted in two accidents on the same day 55 min apart. Although only two were reported, this wild pig was likely the reason for three accidents: the one that killed it and the other two caused by its carcass. Mayer and Johns (2007) reported that the one human fatality associated with WPVCs in their study was caused by a vehicle swerving to avoid an already dead (road-killed) wild pig.

In the U.S., drivers use two-lane roadways for the majority of the total roadway miles they travel (Huijser et al. 2008). Consequently, most (89.7%) animal-vehicle collisions occur on two-lane roads (Huijser et al. 2008). We reported a similar percent of accidents on two-lane roads (i.e., 84.4%) for WPVCs on Georgia roadways. However, the proportion of WPVCs on roadways with four lanes or more (12.2%) was greater than the corresponding share of roadways with four lanes or more (5.3%) in the state. Saxena et al. (2020) found that wild pigs were more vulnerable to collisions with vehicles on four-lane roads as compared to two-lane roads. Those authors also found that the risk of collisions with vehicles on wider roadways was greater for species, like wild pigs, with large group sizes. Given that wild pigs typically occur in social units of two or more individuals (Frädrieh 1974, Mayer and Brisbin 2009) and that wild pigs mostly cross roadways in groups (Saxena et al. 2020; Brieger et al. 2022), several pigs crossing a wide, multi-lane roadway should have an increased risk of at least one of those animals being hit by a passing vehicle.

The percentage of WPVCs that resulted in human injury in this study was higher (9%) than that previously reported in the literature for WPVCs. Jägerbrand and Gren (2018) reported that 0.5% of WPVCs in Sweden result in human injuries, and Sáenz-de-Santa-María and Tellería (2015)

reported a human injury rate of 3.6% for WPVCs in Spain. Within the U.S., Mayer and Johns (2007) stated that 6.1% of WPVCs at a federal property in South Carolina resulted in reported injuries to the drivers and passengers of the vehicles involved. Further research is needed to better understand the magnitude of the human injuries and fatalities that result from these accidents.

Wildlife-related accidents and resulting human injuries are not always caused by a direct hit with an animal. In one study, 62% of all WVCs recorded did not involve a direct hit and, of the 16 human fatalities reported, 31.2% were caused by a near miss (Rowden et al. 2008). Of the rollovers observed in Georgia from this study, all were caused by drivers swerving to avoid a collision with a wild pig. Oversteering and high speeds increase the risk of a rollover (McKnight and Bahouth 2009). Rollovers carry a high risk of mortality and are responsible for nearly one third of all fatalities in motor vehicle accidents (Eichler 2003). In a motor vehicle collision, impacts with trees, posts, or other road objects are the most dangerous (Borkowski et al. 2010); 5% of the WPVC events in the present study resulted in an impact of this type.

Some types of vehicles are more at risk for human injury than others in WVCs (Huijser et al. 2008). For example, both Langley et al. (2006) and Huijser et al. (2008) reported that motorcycle drivers appear to be at a high risk of a fatal event if they collide with an animal, with most fatal deer-vehicle collision crashes involving motorcycles (McClain and Kunkel 2000). Given the lower overall frequency of occurrence in the accidents in our study, motorcycles as well as ATVs would appear to represent a greater risk of human injuries in WPVCs than the other vehicle types. In addition, the vehicles involved in WPVCs may also be related to the behavioral reaction of wild pigs to the different types of vehicles. For example, Brieger et al. (2022) found that wild boar reacted strongly (e.g., moving away from the roadway) when either trucks or buses approached as compared to cars, indicating that larger sized vehicles appear to elicit a behavioral response in wild pigs compared to smaller vehicles.

With recent wild pig populations in the U.S. exceeding 6 million (Mayer 2014; Lewis et al. 2019), WPVCs will continue to occur as pigs persist on the landscape (Groot Bruinderink and Hazebroek 1996; Balčiauskas 2009; Fernández-López et al. 2022). Pakula et al. (2023) noted that, as wild pigs in the U.S. continue to increase in both population size and range, this will likely lead to increased human injury, fatalities, and overall economic impacts due to collisions with this species. Management and lethal control are critical in lessening the detrimental impacts of these collisions by reducing the numbers of these pigs present.

The local harvest of wild pigs by hunters is closely correlated to pig population size and density (Massei et al. 1997, 2015; Merli and Meriggi 2006; Imperio et al. 2010). The

United States Department of Agriculture Animal and Plant Health Inspection Service-Wildlife Services (WS) is the federal agency tasked with mitigating human-wildlife conflicts. Georgia's WS program has been conducting wild pig control since the early 2000's and has increased their annual lethal take ten-fold between 2015 and 2021 (O. L. Stephens, Wildlife Services, personal communication). In addition, Georgia hunters remove many wild pigs from the landscape. The wild pig harvest from hunters alone has increased from 86,422 in 2015 to 138,429 in 2021 (C. Killmaster, Georgia Department of Natural Resources, personal communication, 6 July 2022). Combining these two sources of take, over 700,000 wild pigs were killed in Georgia during the study period; however, both the number of WPVCs and the estimated statewide population size rose during that same period. Strategic and targeted wild pig removal should continue to be implemented to limit wild pig population growth and reduce the risk of WPVCs.

To date, information on WPVCs in the U.S. is limited. Data related to WPVCs are typically (if at all) collected by state transportation and/or law enforcement agencies and private insurance companies. Many of the agencies responsible for managing vehicle collisions do not keep data on the specific wildlife species involved in the crash and these data are often not easily accessible. WVC data held by insurance companies is proprietary and access to those data is at the company's discretion and subject to redactions of pertinent details.

Further research using spatial model techniques is needed to predict the most likely locations for collisions or factors on larger scales that contribute to risk such as road and habitat conditions while accounting for traffic volume, speed limits, road conditions, and density of wild pigs. Better understanding of these factors would aid managers in reducing collisions. Wildlife crossings, fencing, and barriers preventing wild pig road incursions have the potential to reduce injuries, death, and economic damages if implemented properly. Furthermore, the timely removal of road-killed wild pigs can reduce the occurrences of WPVCs and may have prevented several of the incidents included in our study. We recommend that all authorities responsible for protecting human safety on public roads document WVCs accurately with species and geospatial information and make these data available to researchers, road designers and engineers, city planners, wildlife managers, vehicle manufacturers, insurance companies, and many other stakeholder groups. The results of this study provide managers with a more complete picture of the spatial and temporal occurrence of WPVCs, which may aid when dispensing limited resources to where they are needed most to protect motorists.

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Data availability The data used in this study are included as a supplementary material.

Declarations

Ethics approval No approval of research ethics committee was required to accomplish the goals of this study because the data used were only information obtained from the GDOT database.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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