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Decades of Road Mortality Cause Severe Decline in a Common Snapping Turtle (*Chelydra serpentina*) Population from an Urbanized Wetland

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Abstract. — **Road networks threaten biodiversity and particularly herpetofauna, including common snapping turtles (*Chelydra serpentina*), which have an especially slow life history that prevents rapid recovery of populations subjected to road mortality. Cootes Drive is a 2.5-km 4-lane highway that bisects wetland habitat used for nesting and overwintering by snapping turtles. We hypothesized that turtle mortality from collisions with vehicles on Cootes Drive has caused a male bias and a decline in the population as turtles attempt to access habitat on both sides of the road. Capture–mark–recapture studies confirmed a dramatic decline in the turtle population from 941 individuals in 1985 to 177 individuals in 2002, a loss of 764 individuals in only 17 yrs. Using the same data, we also determined that the population has been significantly male-biased since 1985. Using 2009–2016 road mortality data obtained from the Dundas Turtle Watch (a citizen-science program), we completed a population viability analysis using the 2002 population size estimate to isolate the impact of road mortality. We found that this population is at risk of extirpation due to road mortality. The population range overlapped with the Cootes Drive and 7 of the 10 tracked turtles had individual home ranges that overlapped with the road. Our findings support the hypothesis that road mortality has contributed to the dramatic decline in the snapping turtle population in Cootes Paradise Marsh. This population is in jeopardy of extirpation; therefore, exclusion fencing must be installed for an extended distance along both sides of surrounding roads to prevent turtles from crossing the road and to promote their use of existing aquatic culverts.**

Key Words. — **road mortality; home range; population census; Cootes Paradise Marsh; snapping turtle; *Chelydra serpentina;* population viability analysis**

The extensive and dense road network that currently exists in southwestern Ontario means that virtually all wildlife species exist within 1.5 km of a road (Gunson 2010). Road networks pose a threat to biodiversity (Findlay and Houlahan 1997; Clevenger et al. 2003; Beaudry et al. 2010) and particularly to herpetofauna (Gibbs and Shriver 2002; Andrews et al. 2008) by causing point-source mortalities (Baxter-Gilbert et al. 2015). For instance, freshwater turtles are attracted to road shoulders for nesting and thermoregulation (Haxton 2000; Aresco 2005a; Garrah 2012) and often have large home ranges that may require individuals to cross roads to access habitats for mating or overwintering (Ashley et al. 2007; Langen et al. 2009). They also cross roads to forage, disperse from natal sites, locate basking sites, and migrate between seasonal habitats (Gibbs and Shriver 2002; Aresco 2005a; Ashley et al. 2007). Turtles move slowly, so they spend more time on roads than do fast-moving fauna and are therefore more vulnerable to road mortality (Dodd et al. 1989; Garrah 2012).

Female turtles are at particular risk of road mortality owing to nest migrations and attraction to road shoulders for nesting (Jackson and Walker 1997; Aresco 2005a). Unfortunately, nests that are laid on road shoulders tend to fail due to desiccation, compaction, or increased mammalian predation, and when hatchlings do manage to hatch successfully, they face a high likelihood of being struck by vehicles (Ashley and Robinson 1996). A road's "zone of impact" can extend up to 2 km beyond the paved edge (Aresco 2005b) and can result in negative effects such as habitat loss and fragmentation, reduced gene flow (Findlay and Houlanhan 1997; Aresco 2005a; Crawford et al. 2014), and noise and light pollution, as well as increased transmission of invasive species (Andrews et al. 2008). Given how rapidly cities and agricultural lands have developed in southern Ontario over the past 3 decades (Maxwell et al. 2016), growth of road networks associated with this expansion would likely have destroyed and fragmented critical habitat for turtle populations (DeCatanzaro and Chow-Fraser 2010) and possibly resulted in high road mortality. Such an increase in road mortality may threaten entire populations by decreasing reproductive output (Beaudry et al. 2010). Effective mitigation strategies cannot be advanced without a proper study to determine the scale of this threat.

The impacts of roads are particularly negative for snapping turtles (*Chelydra serpentina*) because of their life-history traits, which prevent rapid recovery of populations subjected to road mortality and other threats, resulting in the species being listed as Special Concern in Canada (Committee on the Status of Endangered Wildlife in Canada [COSEWIC] 2008). They exhibit a bet-hedging life history (Stearns 1992) with delayed sexual maturity and low recruitment, high fidelity to nesting and overwintering sites, and a reliance on high adult survivorship to sustain populations (Congdon et al. 1994; Haxton 2000). Snapping turtles are also known for their defensive behavior; when on land, they turn to face the threat to strike by extending their necks instead of moving away from the threat (COSEWIC 2008). This unique, aggressive behavior may make snapping turtles particularly vulnerable to vehicular collisions, as well as head injuries (Sack et al. 2018). Additionally, these behaviors and the species' maligned reputation may result in reluctance of the public to transport snapping turtles for veterinary aid after vehicular trauma (Sack et al. 2018).

We investigated the influence of road mortality on a historically large population of snapping turtles residing in Cootes Paradise Marsh, located on the western edge of Lake Ontario, Canada (Galbraith et al. 1988). Although the subpopulation located in West Pond has been well studied since the mid-1980s, the primary foci of past studies have been on effects of persistent toxic substances on their health, and the negative associated effects on reproductive capacity of turtles (Bishop et al. 1998; de Solla et al. 1998, 2008). Instead, this study focused on the risk to snapping turtles posed by traffic volume on Cootes Drive, a 4-lane highway that bisects the marsh and other surrounding roads. We predicted that traffic on Cootes Drive and adjoining roads would lead to eventual extirpation of this population via road mortality. The overall goal of this study was to assess population trends, examine the impact of road mortality, and to inform the development of recovery strategies for this at-risk population.

METHODS

Site Description. — Our study took place in Cootes Paradise Marsh (CPM), a 250-ha anthropogenically degraded river mouth coastal marsh in the extreme western end of Lake Ontario (Chow-Fraser et al. 1998; Chow-Fraser 2005). Although CPM is situated in a highly urbanized landscape, the marsh is regionally significant owing to its high aquatic and terrestrial biodiversity (Chow-Fraser 1998; Lougheed et al. 2004), including some at-risk species of marsh birds (e.g., least bittern [*Ixobrychus exilis*]; T. Smith and P.C.-F., unpubl. data, 2000) and reptiles. The population of common snapping turtles has been studied since the mid-1980s, primarily in West Pond (WP; Fig. 1; Galbraith et al. 1988). Our study focuses on the western part of CPM, which includes WP, Spencer's Creek, Borer's Creek, and 2 ponds located on land owned and managed by the Hamilton Conservation Authority (P1 and P2; Fig. 1). The marsh complex is completely surrounded by urban lands, including the towns of Dundas, Flamborough, Ancaster, and the City of Hamilton (total population > 500,000 people; Statistics Canada 2016). Within 500 m of CPM, the landscape is > 20% impervious surfaces and the amount increases to 33% and 38% at 1 and 2 km, respectively (Piczak and Chow-Fraser 2019). Cootes Drive is a 4-lane highway (posted limit of 80 km/hr) constructed in 1936 that bisects the wetland complex at the western end and is a main artery from Hamilton to Dundas, with high traffic volume (> 17,000 vehicles/d in 2016; City of Hamilton Traffic Department 2018; Fig. 1).

Some management actions have been implemented to mitigate wildlife road mortality along Cootes Drive. As of the end of 2017, a small portion of the road had been completely fenced with 2-m-high chain link (i.e., just over 300 m on both sides of the road), while 700 m west of Spencer's Creek Bridge was partially fenced with Animex (fencing only on the south side of Cootes Drive; Fig. 1). Approximately 2 km of the roads surrounding CPM, including Cootes Drive, Olympic Drive, and King Street East, remain completely unfenced. There are currently 2 concrete aquatic culverts below Cootes Drive that could serve as eco-passages for turtles (Heaven et al. 2019): one under the Spencer's Creek Bridge and the other at the western terminus of the Animex fencing, which could connect marsh habitat on either side of Cootes Drive (see Fig. 1).

Population Census. — We assembled census data to determine how snapping turtle population size has changed over recent decades and to examine sex ratios. The data were from previous capture–mark–recapture studies that had been conducted in West Pond during 1985 (Galbraith et al. 1988), 1994, 1995, 2002, 2006, 2007, and 2008. In brief, hoop nets were baited with sardines for 14 consecutive days in June and July, during which the first 7 d were used for capture and marking and the last 7 d for recapture. Snapping turtles were either notched (Cagle 1939) or marked with metal tags wired to the shell. We also conducted our own capture–mark–recapture studies in 2017 using the same methods with 14 hoop nets, with bait refreshed daily. We used data from all of these recapture studies and a Cormack-Jolly-Seber model based on the POPAN option in Program MARK (White and Burnham 1999) and package RMark in R 3.3.2 (Laake 2013) to estimate annual population sizes (N). We used capture probability (p), survival (phi), and probability of entry (pent) to estimate population size each year. We applied 2 models to the data, one in which all the aforementioned variables were constant and the other in which they changed over time. We compared models using Quasi-Akaike's Information Criterion (QAIC; Cooch and White 2014), and selected the one with the lowest QAIC to generate the population size estimates for the years 1985, 1994, 1995, 2002, 2006, 2007, and 2008.

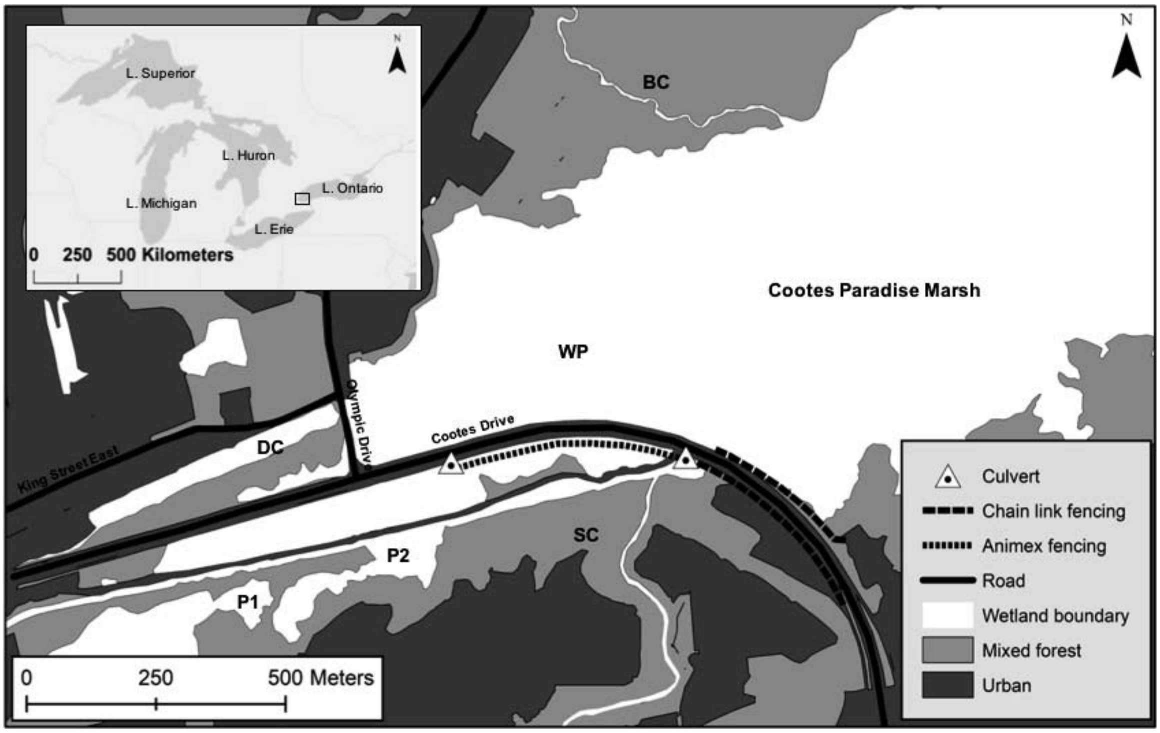

Figure 1. Location of Cootes Paradise Marsh within the Laurentian Great Lakes (inset), Ontario Canada. Snapping turtle sampling locations in western Cootes Paradise Marsh are surrounded by highly urbanized areas. WP = West Pond; DC = Desjardins Canal; BC = Borer's Creek; SC = Spencer's Creek; P1 = Pond 1; P2 = Pond 2. Cootes Drive is the 4-lane highway directly bisecting the wetland.

We used a chi-square goodness-of-fit test to examine adult sex ratios in 1985, 1994, 1995, 2002, and 2017 (not all years were included because of missing data). Additionally, we used a binomial generalized linear model, which included number of males and females as variables and years as a random effect, to determine if sex ratio became male-biased over time.

Road Mortality and Population Viability Analysis. — Dundas Turtle Watch (DTW) is a long-standing and well-recognized citizen-science program that monitors wildlife road mortality on Cootes Drive and surrounding roads. This program has been operational since 2009 and involves ≥ 2 volunteers walking a route to survey Cootes Drive, Olympic Drive, and King Street East (Fig. 1). In addition to recording any dead wildlife on the road, volunteers assist animals across the road if they happen to find them crossing, thereby averting road mortalities. In 2009 and 2010, the survey route was completed once every other week from June to September, and from 2011 to 2016 surveys were completed at least weekly from June to September. We used a Poisson generalized linear mixed model to determine if number of total adult turtles found differed with varying survey effort (number of surveys per year). We included year (2009–2016) as a random effect to control for lack of independence.

Using the DTW road mortality survey data (2009–2016; Table 1), we conducted Population Viability Analysis (PVA) in Vortex 10.0 (Lacy 1993) with life-history parameters collected from the literature (Supplemental 1; all supplemental material is available online at https://doi.org/10.2744/CCB-1345.1.s1). We used life-history parameters from the most recent literature available from both CPM and other northerly snapping turtle populations in the PVAs (Supplemental 1). We conducted 3 different road mortality scenarios, in which the harvest function was set to the minimum, mean, and maximum number of adult turtles observed annually on roads by DTW (Table 1). We included turtles saved by DTW volunteers because without intervention, it was highly likely these individuals would have been struck by cars, given that Aresco (2005b) found 98% of turtles crossing a 4-lane highway were hit by automobiles. The initial population size was set to the most recent population estimate from 2002 and carrying capacity was set to a quasi-extinction threshold (assuming equal sex ratios) of 10 individuals therefore permitting recruitment (Enneson and Litzgus 2009). We ran each model for 500 yrs using 500 iterations to account for individual longevity and long generation times (Congdon et al. 1994). The default value for inbreeding depression was used and the population was considered extinct when there was only one individual remaining. These PVAs generated population growth rates (r), extirpation probability, mean time to first extirpation, and final population size.

Field Methods. — We opportunistically caught 10 adult snapping turtles (6 males, 4 females) by hand in April 2017. We collected biometric data and determined sex using the length ratio of both the femoral and anal

Table 1. Findings from Dundas Turtle Watch road mortality surveys conducted on Cootes Drive, Olympic Drive, and King Street East, Ontario, Canada. We used the lowest number of observed dead adult common snapping turtles from 2009 ($n = 1$), highest number of encountered adult turtles from 2012 ($n = 12$), and mean total encountered turtles ($n = 8$) as harvest functions in the population viability analyses.

Year	No. of surveys	No. of deceased adult turtles/yr	No. of saved adult turtles/yr	Total no. of encountered adult turtles annually
2009	17	1	7	8
2010	18	2	9	11
2011	42	3	8	11
2012	24	0	12	12
2013	44	3	7	10
2014	73	0	1	1
2015	71	2	3	5
2016	66	3	4	7

scutes compared with the precloacal length (Petokas 1979). An equal number of turtles were captured from waterbodies on either side (north and south) of Cootes Drive and turtles captured directly on roads were not radiotagged. We fitted each turtle with a radiotransmitter (10 g; Holohil, Carp, ON, Canada) using epoxy putty, and ensured that the total weight of the transmitter and epoxy putty did not exceed 5% of the turtle's body mass and that the attachments were colored black to provide camouflage. Immediately after tagging, we released each turtle at its initial capture site. Throughout the 2017 and 2018 seasons, we used a 3-element Yagi antenna (Wildlife Materials International, Murphysboro, IL, USA) and a Lotek Biotracker Receiver (Lotek Wireless, Newmarket, ON, Canada) to locate tagged turtles. Radiotracking was conducted from April to September in 2017 and from April to August in 2018, with each individual being located at least once per week. Each time a turtle was located, we recorded the Global Positioning System location and type of habitat occupied by each turtle.

Spatial Analysis. — We conducted an incremental area analysis to determine data sufficiency prior to calculating home range size for each radiotracked individual. The home range (based on 100% Minimum Convex Polygon; MCP) of 3 locations was first calculated and then recalculated for each subsequent location added. The home ranges were plotted against the number of locations until an asymptotic slope could be visually confirmed. According to Jaeger and Cobb (2012), ≥ 30 points are required to reach this asymptote to indicate a sufficient number of relocations has been achieved. Based on the asymptotic shape of curves in the incremental area analysis (Supplemental 3), we were satisfied that we had adequately located all tagged individuals during the study period to estimate a valid home range for each. We collected a minimum of 30 locations/turtle (mean of 34.5 relocations; Supplemental 4). At the population level, we had 411 locations from the tracking program and 101 locations that were from encounters with additional untagged turtles during 2017 and 2018. To estimate size of the population and core ranges, we constructed MCPs that included locations of all radiotagged and untagged snapping turtles that we encountered during our surveys, including those of adults and juveniles.

We estimated home range sizes at the individual and population levels using an extension of R 3.3.2 (version 5.0; R Core Team 2018) called Reproducible Home Range (Signer and Balkenhol 2015) in ArcGIS 10.5 (ESRI, Redlands, CA). Estimations of individual home ranges did not include nesting migrations of the tagged female turtles. The MCPs were calculated at the 50% (core range) and 100% level for individuals and the population. We also calculated population and core ranges for behavioral seasons in 2017 only: prenesting (1 April–12 June), nesting (13 June–4 July), and postnesting (5 July–20 September). Prenesting season was defined as the period when we started radiotracking to the time when the first nest site was identified during nesting surveys. The nesting season was delineated by the period when the first and last nests were found during surveys. Postnesting season began after the last day of the nesting season and until the first day of the overwintering period (once all tagged turtles migrated to overwintering locations).

We calculated the area of overlap (in hectares) between individual and population ranges with Cootes Drive, King Street East, and Olympic Drive. Based on chronology of data points, we determined the number of presumed road crossings, which we defined as an instance when a turtle was found on one side of the road and then on the opposite side when radiotracked. We refer to this as a presumed road crossing because we do not know if the turtle had actually travelled over the road or under the road via culverts.

RESULTS

The estimated size of the snapping turtle population in western CPM declined by almost 80%, from 941 individuals in 1985 to only 177 in 2002 (Fig. 2). The Cormack-Jolly-Seber model with the lowest AIC (57.14) included constant variables (pent, phi and p). We could not include the 2006–2008 or 2017 capture–mark–recapture data because the number of marked recaptures during the recapture period was insufficient (only one marked recapture in 2006 and none in 2007, 2008 or 2017). Although we were unable to obtain a population size estimate in 2017, we encountered 65 individual snapping turtles in western CPM during that year, 22 of which had been previously notched; therefore, we found 43 unmarked individuals. It had been almost 10 yrs since the previous capture–mark–recapture studies and during the course of our field sampling we notched these 43 individuals. The population of snapping turtles has not become increasingly male-biased since 1985 ($p > 0.564$);

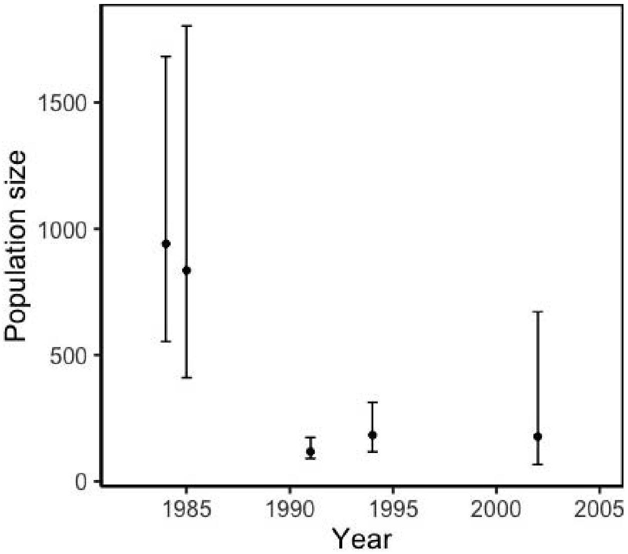

Figure 2. Estimated snapping turtle population size (± 95% confidence intervals) in the western portion of Cootes Paradise Marsh from 1985 to 2002 using Cormack-Jolly-Seber models.

however, sex ratios across all years significantly deviated from parity, indicating male biases (Table 2).

Road survey effort had a significant negative effect on the total number of turtles found ($Z = -2.615$, $p < 0.008$) such that increasing survey effort did not result in additional turtles encountered on the road (Supplemental 2). From 2009 to 2016 inclusive, the minimum number of encountered adult turtles was 1/yr. The highest number of observed turtles encountered on the road across all survey years was 12 in 2012, while the mean number of turtles found per year was 8.15 ± 1.31 SE (Table 1). The minimum road mortality scenario resulted in a very small positive population growth, while both the mean and maximum road mortality scenarios resulted in negative population growth (Fig. 3; Table 3). For the minimum mortality scenario, there was a 35% probability of extirpation and the mean time to first extirpation was 258.8 yrs. In both the maximum and mean scenarios, there was an extirpation probability of 100% within 500 yrs and a mean time to first extirpation of 23.0 and 17.9 yrs, respectively (Table 3). Therefore, road mortality of adult snapping turtles increased extirpation risk in CPM.

Table 2. Sex ratios of the common snapping turtle (*Chelydra serpentina*) sampled in Cootes Paradise Marsh, Ontario, Canada. * = sex ratio deviates significantly from parity.

Year	No. of females	No. of males	Percentage of sample that is male	p
1985	25	90	78	< 0.001*
1994	57	80	58	< 0.05*
1995	70	120	63	< 0.001*
2002	9	13	59	< 0.02*
2017	17	40	70	< 0.003*

We calculated a population range of 288.8 ha and a core range of 22.8 ha (Fig. 4). Both population and core ranges overlapped with surrounding roads, including Cootes Drive, Olympic Drive, and King Street East. In general, the majority of snapping turtles that had been caught in the southern Hamilton Conservation Area ponds (Ponds 1 and 2) moved north toward CPM after capture; by comparison, all turtles originating from West Pond remained there and did not cross Cootes Drive during the active season. However, 2 males that had been caught in West Pond moved throughout the Desjardins Canal during the study.

Exclusive of nesting migrations, the mean female ranges (core range and home range of 1.0 and 15.3 ha, respectively) were smaller than those of males (core range and home range of 12.4 and 49.9 ha, respectively; Supplemental 4). Three individual core ranges overlapped with surrounding roads and 7 individual home ranges overlapped with surrounding roads (specifically, Olympic Drive, Cootes Drive, and King Street East). The majority of the home ranges overlapped with portions of surrounding roads that were either unfenced or only partially fenced, which resulted in turtles presumably crossing the road 3 times during the 2017 and 2018 seasons (Supplemental 4) with males crossing more often (mean = 3.8 ± 3.4 SE) than females (mean = 1.8 ± 2.3 SE). Although turtles were most likely to interact with roads during the nesting season because overlap between population core range and roads was larger (1.8 ha) compared with the pre- and postnesting seasons (1.2 and 0.7 ha, respectively), overlap with roads to some extent occurred at both spatial scales and throughout the active season, putting all turtles at risk of road mortality to some degree.

DISCUSSION

The western end of Cootes Paradise Marsh (CPM) is located close to the town of Dundas and the marsh is surrounded by several busy roads, including Cootes Drive (see Fig. 1), which in 2016 had a mean daily traffic volume of > 17,000 vehicles (City of Hamilton Traffic Department 2018). The population in Dundas has grown steadily over the past 3 decades, increasing by 25% from 20,000 to 25,000 between 1980 and 2010. The snapping turtle population in western CPM had once been one of the densest populations in Ontario (66 individuals/ha in the mid-1980s; Galbraith et al. 1988) with an estimated population size of 941 in 1985. By the early 2000s, the population had declined by almost 80% to 177. Although we were unable to reliably estimate the population in 2017 because of insufficient number of captures, we conducted exhaustive surveys on a weekly basis and found 65 (22 previously tagged) individual common snapping turtles in western CPM. It has been well documented that turtle populations subjected to road mortality often become increasingly male-biased because female turtles are more vulnerable to road mortality due to nest migrations (Haxton 2000; Aresco 2005a; Steen et al. 2006). Despite this expectation, the population in CPM has not become increasingly male-biased over the past 3 decades, perhaps because it had already been significantly male-biased since at least 1985.

Using population viability analyses, we showed that increases in annual adult mortality resulted in increased extirpation risk, which is consistent with previous studies (Brooks et al. 1991; Congdon et al. 1994; Aresco 2005b; Enneson and Litzgus 2009; Midwood et al. 2014; Zimmer-Shaffer et al. 2014; Keevil et al. 2018). In the 2 severe scenarios (maximum, 12; mean, 8), the mean time to first extinction was ~ 20 yrs from 2002. We also found that in the mean and maximum road mortality scenarios, the probability of extirpation was 100%, while with the minimum scenario, the extirpation risk was 35%. International Union for Conservation (IUCN) criteria dictate that that a population is viable if the extirpation risk is < 10% (IUCN 2011); by that standard, the CPM population may be in imminent danger of extirpation. Midwood et al. (2014) found that loss of a single adult female snapping turtle per year could decrease the population to zero within just 200 yrs. Furthermore, Congdon et al. (1994), found that an increase in snapping turtle mortality by 0.1 adult/yr could halve a population in just 20 yrs.

It is likely that the number of turtles observed (dead and alive) on surrounding roads of CPM was an underestimation of the true number of road mortality occurrences. For instance, our estimates do not account for eventual mortalities of animals that manage to move off the road after being struck (Dodd et al. 1989). Scavengers and road maintenance (e.g., road-side lawn mowing) can also reduce the number of carcasses encountered during surveys and lead to an underestimation of mortality (Crump et al. 2016). Additionally, use of data generated by citizen-science programs has benefits, but also many challenges. There was lower effort in the early years of the program while DTW became more established as an organization. There were also some inconsistencies in how the large number of volunteers recorded their observations. Even so, citizen-science programs have many benefits, including community involvement, educational awareness of conservation issues, and in-kind data collection, without which this study would not have been possible.

Despite the relatively small human population of 25,000 in Dundas, the traffic volume on Cootes Drive exceeds 17,000 vehicles/d (City of Hamilton Traffic Department 2018). This traffic volume does not include the number of cars on adjacent roads (e.g., Olympic Drive and King Street East). Most other studies that have examined road mortality of turtle populations reported

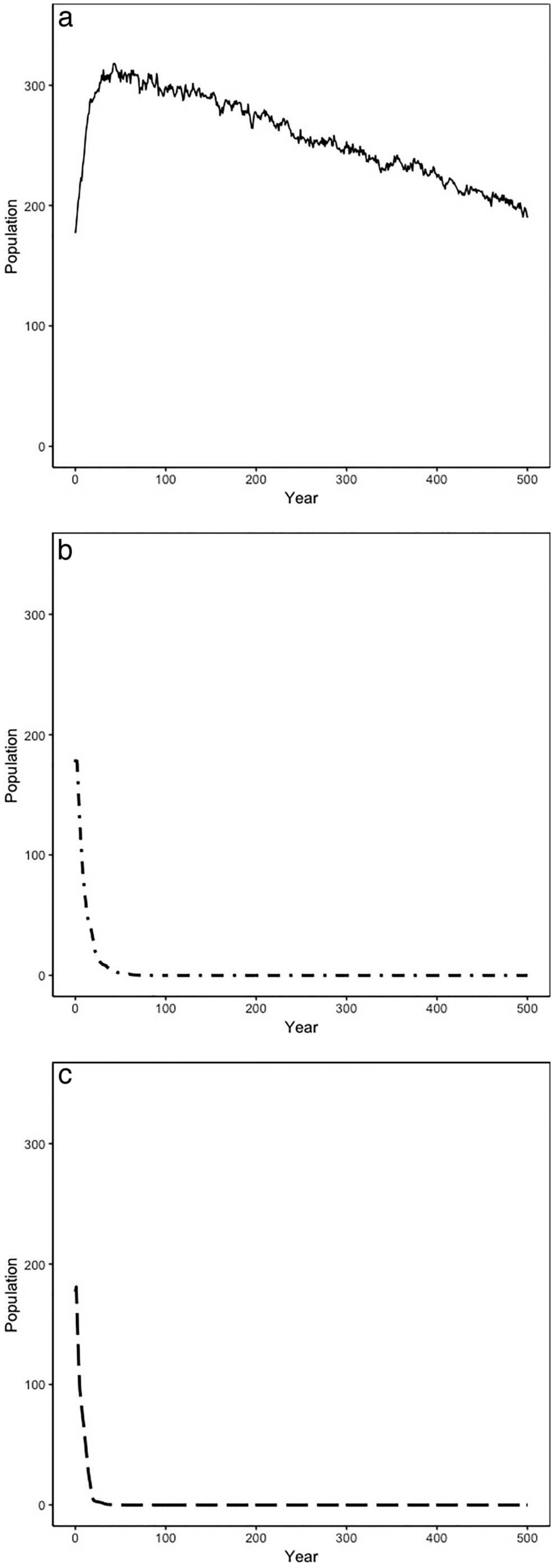

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Figure 3. Impact of adult road mortality on the snapping turtle population in Cootes Paradise Marsh, based on population viability analyses with (a) minimum, (b) mean, and (c) maximum mortality scenarios.

Table 3. Impact of adult road mortality on the common snapping turtle (*Chelydra serpentina*) population in Cootes Paradise Marsh, Ontario, Canada, based on population viability analyses over 500 yrs for 3 road mortality scenarios, with standard deviations.

	Road mortality scenarios		
	Minimum (1)	Mean (8)	Maximum (12)
Population growth rate	0.026 ± 0.32	−0.122 ± 0.24	−0.157 ± 0.20
Probability of extinction	0.35 ± 0.02	1.00 ± 0	1.00 ± 0
Final population size	189.84 ± 175.23	0 ± 0	0 ± 0
Mean no. of yrs to first extinction	258.8 ± 142.58	23.0 ± 9.92	17.9 ± 4.08

substantially lower traffic volumes, ranging from a few thousand cars per day (Ashley and Robinson 1996; Glista et al. 2008; Crump et al. 2016) to almost 14,000 cars/d (Langen et al. 2009). The only study reporting higher traffic volumes than ours (> 21,500 vehicles/d) occurred in Lake Jackson, Florida, where only 2% of the turtles crossing a 4-lane highway made it across without getting hit by a vehicle (Aresco 2005b). Therefore, it is not surprising that the snapping turtles on Cootes Drive faced certain death when they tried to access habitat on opposite sides of Cootes Drive, especially because 2.7% of drivers have been found to intentionally hit turtles in southern Ontario (Ashley et al. 2007).

We inferred that turtles had crossed a road (either walking over the road or under the road via a culvert) when turtles were tracked to habitat on opposite sides of the road over a relatively short period (at most 1 wk). Although we monitored movements of only 10 individuals, it is clear that radiotagged turtles used habitat on both sides of Cootes Drive. Fortunately, there are already 2 culverts in place that turtles could use for safe movement (Fig. 1), although we did not observe any of the tagged turtles using these during 2018 (P.C.-F., unpubl. data, 2016). Data from a previous study conducted in CPM support these findings (Pettit et al. 1995), indicating that the population has been at risk for multiple decades.

In addition to road mortality, persistent toxic substances present in CPM may have resulted in decreased hatching success, increased deformities (de Solla et al. 1998), and abnormal development in snapping turtle hatchlings (Bishop et al. 1998), all of which could have contributed to population declines. Additionally, prior to April 2017, Ontario permitted the legal hunting of up to 2 adult snapping turtles/d (Fish and Wildlife Conservation Act 1997). We also recently documented that ranavirus resulted in the mortality of at least one snapping turtle in CPM (McKenzie et al. 2019). Other potential threats include persecution by people, high nest depredation by meso-predators that are common in urbanized areas, water-quality pollution (from the sewage treatment facility at the

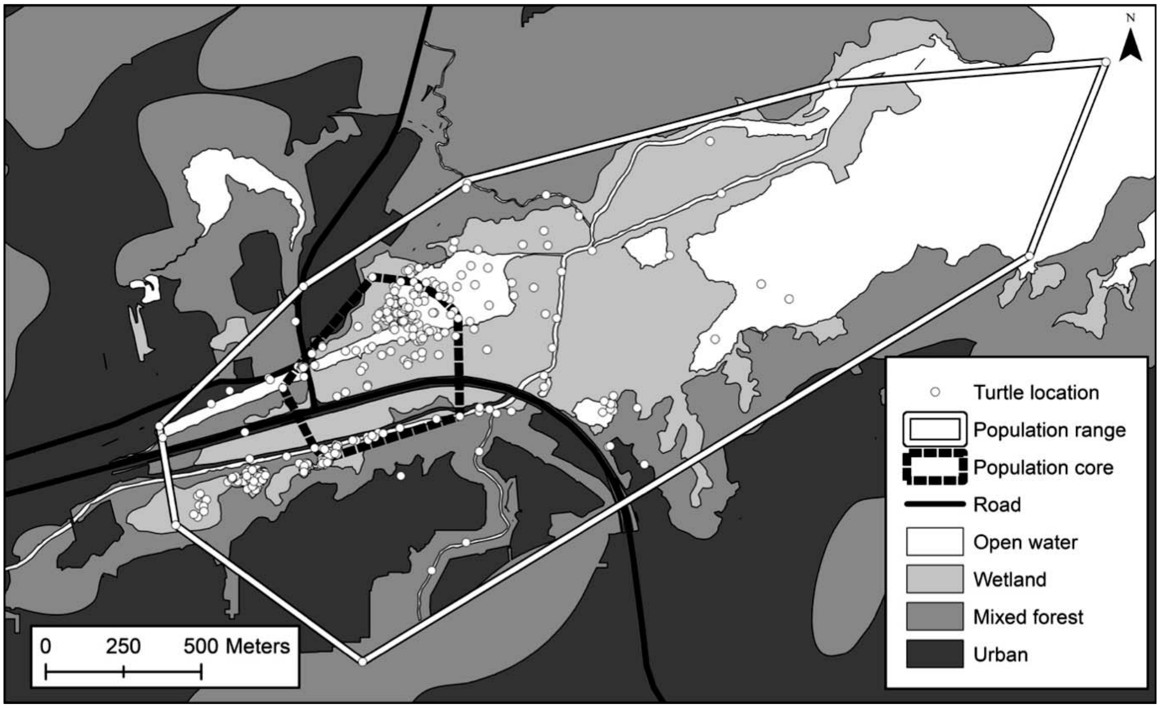

Figure 4. Minimum convex polygon (MCP) of population range (estimated by the 100% MCP) and core range (estimated by 50% MCP) for the snapping turtle population in western Cootes Paradise Marsh. Both the population and core range estimates are shown to overlap with surrounding roads (Cootes Drive, King Street East, and Olympic Drive).

western end of the Desjardins Canal), and loss and fragmentation of critical habitat, especially following establishment of invasive common reed (*Phragmites*) in southern Ontario (COSEWIC 2008). Therefore, road mortality is only one of the many threats that are contributing to the decline in the snapping turtle population.

It is instructive to note that we found road mortality alone to severely reduce the snapping turtle population, even without taking into account any of the other threats discussed above. Loss of adults in other freshwater turtle species have shown similar results. Adult survival of the diamondback terrapin (*Malaclemys terrapin*) and the spotted turtle (*Clemmys guttata*) had the greatest influence on population growth, and minimizing adult road mortality was deemed to be an important component in recovery plans for these species (Enneson and Litzgus 2008; Crawford et al. 2014).

Spatially, the snapping turtles remain at risk of being killed or injured by cars along unfenced and partially fenced roads because of the large overlap between individual and population ranges with adjacent roads. To reduce further road mortality along surrounding roads, it is imperative that complete exclusion fencing (on both sides of the road) be installed in areas within the population range. Only complete fencing mitigates against collisions with cars; partial fencing may actually increase reptile abundance on roads and did not perform better than road sections with no fencing (Markle et al. 2017). The integrity of exclusion fencing is extremely important (Baxter-Gilbert et al. 2015; Markle et al. 2017); therefore, we do not recommend using silt fencing or geotextile plastic because of their relative fragility and vulnerability to damage (ultraviolet damage, holes and rips; Aresco 2005b; Baxter-Gilbert et al. 2015; Markle et al. 2017). Although durable fencing material and design have high upfront costs, they are known to be more effective and longer lasting (Markle et al. 2017; Jakes et al. 2018). Should fence integrity be compromised and allow turtles to access the road, they may become entrapped by the fencing, and become exposed to additional risk (Wilson and Topham 2009; Baxter-Gilbert et al. 2015; Markle et al. 2017). Additionally, where fences end abruptly, turtles are able to access the road at the terminus of the fencing and therefore fencing should be angled and curved back into surrounding habitat to prevent individuals from circumventing the structure (Aresco 2005b; Markle et al. 2017). Although there are 2 existing aquatic culverts below Cootes Drive that allow turtles to cross safely under the road, complete fencing is required to direct turtles toward the culverts' openings.

Based on the results of the PVAs, it is likely that the large historical decline in the turtle population was caused primarily by road mortality on surrounding roads. Owing to their life-history traits, it is very difficult for snapping turtle populations to compensate for the loss of adults via anthropogenic stress and these situations can put populations in danger of extirpation (Cunnington and Brooks 1995; Keevil et al. 2018). Snapping turtles do not respond to density-dependent threats by increasing recruitment or immigration, so they often have a very slow recovery following population declines (Brooks et al. 1991). Keevil et al. (2018) found that snapping turtle populations failed to recover and had low abundances after facing a prolonged period of mortality. Without immediate mitigative action to eliminate road mortality on roads around Cootes Paradise Marsh, it is likely that the snapping turtle population will continue to dwindle and eventually become extirpated.

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