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Assessment of critical habitat for common snapping turtles (*Chelydra serpentina*) in an urbanized coastal wetland

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Abstract
Critical habitats such as nesting areas and overwintering sites are specific areas used by organisms to carry out important life functions. In many urbanized centers, critical habitats of at-risk species have often become degraded and/or fragmented because of human activities. Such is the case for the population of common snapping turtles (*Chelydra serpentina*) in Cootes Paradise Marsh, a highly urbanized ecosystem located at the western tip of Lake Ontario. In addition to these threats, mortality from collisions with cars on a four-lane highway at the western end of the marsh has greatly reduced wildlife populations. Here, we examine long-term changes in critical habitat distribution that has accompanied urbanization of Cootes Paradise Marsh from 1934 to 2010. We delineated potential nesting habitat for snapping turtles in 7 digitized aerial photos, using literature information and 2017 nesting surveys as guides. Between 1934 and 2010, total area of potential nesting habitat decreased by almost 50%. Nesting surveys confirmed that snapping turtles were disproportionately using created nesting mounds and this suggests that availability of natural nesting habitat is limited. We also radio tracked 11 snapping turtles to identify use of overwintering habitat. Temperature loggers monitored in-situ water temperatures at each turtle's location and other unconfirmed habitats. The snapping turtle population overwintered in a wide range of upland terrestrial habitats and we found consistent characteristics regarding water temperature across both confirmed and unconfirmed sites, therefore suggesting overwintering habitat may not be limiting within the marsh.

Keywords Snapping turtle · *Chelydra serpentina* · Urban impacts · Critical habitat · Overwintering · Nesting

Introduction

Critical habitat can be defined as habitat that is essential for an organism to carry out necessary life functions such as reproduction/mating, overwintering, migration, feeding or rearing (Government of Canada 2009). To effectively manage and conserve wildlife populations, particularly those living in an urban center, managers must know the species' home range and location of critical habitat (Markle and Chow-Fraser 2017). Where freshwater turtles are concerned, in addition to identifying critical habitat, it is also important to identify anthropogenic threats that may be contributing to habitat alteration, destruction or fragmentation.

Common snapping turtles (*Chelydra serpentina*) are long-lived organisms whose life-history strategy include delayed sexual maturity, reliance on low adult mortality, and low recruitment, traits that leave populations at risk to alteration of critical habitat, a primary adverse effect of urbanization (Congdon et al. 1994; COSEWIC 2008). At both the federal and Ontario provincial level, snapping turtles have been designated as Special Concern (ECCC 2016). For common snapping turtles, critical habitat includes nesting and overwintering habitat, both of which are important for maintaining population viability (COSEWIC 2008). The reproductive rate of snapping turtles is extremely low; less than 0.1% of eggs of snapping turtles hatch and survive to sexual maturity, even in an undisturbed setting such as Ontario's Algonquin Provincial Park (COSEWIC 2008). Therefore, presence of suitable nesting habitat is essential for supporting recruitment and preserving populations. The oviposition site is important to nesting success and can have important phenological implications for hatchlings including survival, development, and growth rates (Kolbe and Janzen 2002). In urban, modified, and/or polluted environments which have a host of anthropogenic impacts,

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reproductive success and recruitment can be even lower and seriously impair population stability (Thompson et al. 2017).

Suitable nesting habitat is characterized by well-drained soil, minimal vegetative cover and open canopy for sun exposure (Dekker 2015; Thompson et al. 2017). In natural settings, nesting sites can include abandoned beaver lodges, muskrat houses, sandy or rocky shorelines (Obbard and Brooks 1980). In many altered and urbanized landscapes that lack suitable nesting sites, snapping turtles may be attracted to use suboptimal or unsafe sites such as shoulders of roads (Haxton 2000) or agricultural fields (Pappas et al. 2013). Such areas are ecological sinks associated with low survivorship of eggs and hatchlings (Mui et al. 2015). Specifically, on roads sides, survival factors can include high road mortality, soil compaction and anthropogenic pollution (Paterson et al. 2012). In agricultural fields, nests could be flooded via irrigation and/or damaged or destroyed during the tilling process, both also resulting in decreased nest success (Thompson et al. 2017). In highly urbanized settings, proactive identification of nesting habitat and measures to steer turtles away from dangerous habitats, such installation of created nesting mounds are common strategies in conservation programs (Grosse et al. 2015; TRCA 2018).

At northern latitudes, selection of appropriate overwintering sites is very important to the point of being predictive of life or death for individual snapping turtles. Snapping turtle survival during harsh winter conditions is reliant on individuals selecting sites that a) provide protection from freezing water temperatures, b) afford concealment from predation and c) deliver access to dissolved oxygen (DO) (Brown and Brooks 1994). Snapping turtles spend nearly half the year at overwintering sites (Strain et al. 2012) and it is critical that these areas possess these three conditions necessary to increase winter survival probabilities. Prolonged exposure to sub-zero temperatures can result in turtles freezing to death, given that the freezing temperature of body fluids in turtles is −0.6 °C (Costanzo et al. 2006). Ideally, overwintering sites will have water temperatures sufficiently cool to support a reduction in metabolic costs (Markle and Chow-Fraser 2017; Paterson et al. 2012), but not so cold as to result in freezing. During overwintering, turtles may also be subjected to anoxic conditions and must use anaerobic respiration; however, this leads to lactic acid accumulation (Meeks and Ultsch 1990; Reese et al. 2002). Overwintering sites must therefore provide sufficient DO to minimize risk of death via acidosis.

As discussed above, freshwater turtles are confronted with a trade-off between death by acidosis or by freezing. If they select sites with muddy substrate, they could avoid freezing but may encounter low DO levels that can result in acidosis (Brown and Brooks 1994; Paterson et al. 2012; Reese et al. 2002). Sites that are above the sediment surface could have higher DO levels but may freeze during the winter (Brown and Brooks 1994). Finally, to the extent that snapping turtles reduce their metabolic activity, they are increasingly vulnerable to mammalian depredation by a variety of predators including mink (*Neovison vison*), otters (*Lontra canadensis*) and black bears (*Ursus americanus*) (Ultsch 2006). Because of all these dimensions, snapping turtles can overwinter in a wide range of shallow aquatic sites; identifying the physical characteristics (especially depth & ambient water temperature) that are most important for overwintering habitats can assist conservation agencies in developing recovery plans for this at-risk species.

Cootes Paradise Marsh (CPM) is an urbanized river mouth coastal marsh located in the extreme western end of Lake Ontario, Hamilton, Ontario, Canada (Chow-Fraser 1998). This marsh has been subjected to a range of anthropogenic stressors including urban and agricultural development, invasive species (common carp, *Cyprinus carpio* and common reed, *Phragmites australis*), external and internal loading and regulation of water levels (1963) (International Joint Commission 1961) that have resulted in loss of emergent and submergent vegetation (Chow-Fraser 2005; Lougheed et al. 2004; Thomasen and Chow-Fraser 2012). Additionally, road mortality associated with Cootes Drive, a four-lane highway that bisects the wetland, is hypothesized to have dramatically decreased snapping turtle population size over in recent decades and created unsafe nesting sites along roadsides. Taken together, these represent direct or indirect threats to the viability of the remaining population of snapping turtles in CPM.

Preserving a population of snapping turtles requires sufficient recruitment through viable nesting habitat and high adult survival, which partially depends on suitable overwintering habitat (Dekker 2015). To promote recruitment and winter survival and therefore minimize risk of population extirpation, it is essential to identify and protect critical habitat in such urbanized and often anthropogenically degraded settings. The goal of this study is to assess and identify long-term changes in available nesting and overwintering habitats for the sub-population of snapping turtles located at the western end of CPM. We will examine changes in the amount of potential nesting habitat over seven decades including data from before and after the establishment of Cootes Drive in 1936. We will also use information on current nesting and overwintering habitat to determine important characteristics of these critical habitats. Identifying and mapping critical habitat can inform management and conservation agencies on strategies to conserve the remaining snapping turtle population in CPM.

Methods

Site description

Cootes Paradise Marsh (CPM) is a provincially significant, 250-ha river mouth coastal wetland located in the extreme western end of Lake Ontario (Fig. 1). While highly productive and supportive of biodiversity, CPM has been subjected to long-term negative impacts of agricultural and urban development associated with the towns of Dundas, Flamborough, and Ancaster and the City of Hamilton that border the wetland complex (Chow-Fraser 1998). Anthropogenic impacts have included degradation and loss of habitat, nutrient and sediment enrichment, regulation of Lake Ontario water levels beginning in 1963 (International Joint Commission 1961), and invasions of non-native species. Water-level regulation led to die-back of the native cattail (*Typha latifolia*) and paved the way for invasion of reed manna grass (*Glyceria maxima*) and the invasive haplotype of common reed (*Phragmites australis*) (Wei and Chow-Fraser 2006). Sediment and nutrient enrichment from wastewater effluent led to water-quality degradation, loss of submergent vegetation and concomitant dominance by the non-native common carp (*Cyprinus carpio*) (Chow-Fraser et al. 1998).

Of all the ecosystem stressors on CPM, however, the construction of Cootes Drive in 1936 likely had the most severe consequences for the turtle populations. This is a busy four-lane arterial road/highway connecting Hamilton to the town of Dundas, which bisects the western portion of CPM into West Pond to the northwest and two ponds on Hamilton Conservation Authority (HCA) land to the southeast (see Fig. 1). With a posted speed limit of 80 km/h, it has been hypothesized that vehicular traffic has been responsible for a relatively high mortality of freshwater turtles and other wildlife that once inhabited the marsh ecosystem.

Nesting habitat

We obtained historic air photos of CPM complex to study how potential suitable nesting habitat has changed over the past century. Photos taken in 1934, 1959, 1972, 1978, 1999, 2002 and 2010 were imported into ArcGIS 10.5 (ESRI, Redlands, California, USA; see Table 1). To delineate the outer boundary of the habitat mapping, we digitized the shoreline of CPM using the 2010 imagery and applied a 500 m buffer to ensure we captured maximum distance a female snapping turtle would travel on land to a nesting site (Congdon et al. 1987; Paterson et al. 2012). We applied this footprint to all photos across years to ensure we had the same spatial extent with which to conduct a change detection analysis. Within the 500-m shoreline buffer, habitats were manually digitized at a map scale of 1:1500. Since there is no available information of what had been used as nesting habitat in CPM, we created a ruleset to delineate and classify potentially suitable nesting habitats based on published descriptions of nesting habitat for snapping turtles, which includes open areas with loose soil and minimal vegetation (Dekker 2015; Steyermark et al. 2008). To ensure this protocol could be applied to all photos, we used the 1934 and 2010 images to guide the ruleset creation. Furthermore, we modified habitat ecosites from the Ecological Land Classification for Southern Ontario system (Table 2). We then used ArcGIS 10.5 to delineate different habitat classes and calculated the total area of all habitat types for each year. Finally, we conducted a change detection analysis of the 1934 and 2010 images to determine the type of habitat lost, gained or left unchanged.

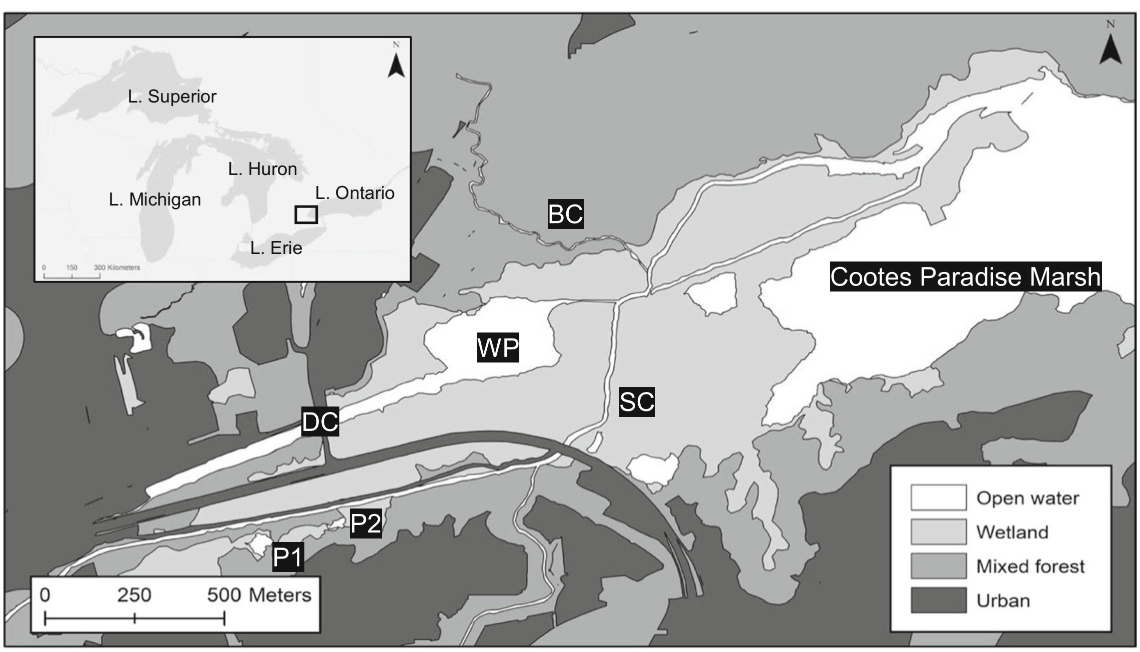


Fig. 1 Location of sampling locations in Cootes Paradise Marsh and surrounding upland habitat. Cootes Paradise Marsh open water, WP = West Pond, DC = Desjardins Canal, BC = Borer's Creek, SC = Spencer's Creek, P1 = Pond 1, P2 = Pond 2. Inset shows the location of CPM within the Laurentian Great Lakes

Table 1 Dates of orthophotos used in this study to map potential nesting habitat for snapping turtles in CPM. Resolution refers to size of pixel

Year	Type	Spectral type	Resolution (cm)	Season	Source
1934	Orthophoto	B&W	260	Leaf on	National Air Photo Library (Canada) 1934
1959	Orthophoto	B&W	125	Leaf off	Spartan Air Services Ltd. 1959
1972	Orthophoto	B&W	55	Leaf on	Lockwood Survey Corporation ltd. 1972
1978	Orthophoto	B&W	50	Leaf on	Ontario. Ministry of Natural Resources, 1978
1999	Orthophoto	True colour	12.5	Leaf on	North West Geomatics Canada Inc. 1999
2002	Orthophoto	True colour	20	Leaf off	City of Hamilton 2002
2010	Orthophoto	True colour	20	Leaf off	Southwestern Ontario Orthophotography Project (SWOOP 2010)

Nesting surveys were conducted in the morning between the hours of 8:00 AM to noon by walking a designated route from May 23rd to July 7th 2017. We created transects along the roadside and surveyed both sides of the transect; in larger fields that were logistically unfeasible to survey completely, we applied a regular grid pattern (~ 2 m) to conduct nest surveys. We noted the GPS of each location, date and time of the survey and any evidence of nesting activity (i.e. presence of a nesting mound, female turtle, eggs or egg shells). Data about the macrohabitat such as percentage vegetation cover and weather conditions were also recorded. Potential nesting habitat type of the surveyed area was classified according to modifications from the Ecological Land Classification for Southern Ontario, which included 5 classes: anthropogenically maintained fields, natural fields, gravel, shoreline and agricultural fields (Table 2). We calculated the percentage of nesting observations of each habitat type and compared it to the percentage of habitat types within the survey area. To determine if nest use strayed from random (even use of all habitat types) we subjected the data to a Chi-squared test for given probabilities. Additionally, to examine nest density, we compared distance to next nearest point in ArcGIS 10.5 of nest survey observations and random points. We included the same number of random points as nesting observations ($n = 84$) and they were confined to the nest survey area.

Table 2 Potential nesting habitat types in CPM based on manually classified orthophotos using the Ecological Land Classification for Southern Ontario

Habitat	Description
Anthropogenically maintained field	Areas with grass for human use including lawns, sports fields
Natural field	Open, natural, terrestrial area with minimal tree cover
Gravel	Areas with gravel, minimal vegetation
Shoreline	Land adjacent to body of water, with minimal vegetation
Agriculture	Active or retired agricultural fields

We then completed a Student's t test on the distances to next nearest point in R 3.3.2 (version 5.0) (R Core Team 2018). Finally, we calculated nest density using the nesting survey observations and total survey area (28.9 ha).

Overwintering habitat

We opportunistically captured eleven snapping turtles by hand soon after they emerged from overwintering during April 2017, notched them (Cagle 1939) and outfitted them with radio transmitters (Lotek Wireless, Newmarket, ON, Canada, 10 g) using an Ontario Ministry of Natural Resources and Forestry (OMNRF) approved epoxy putty. We ensured that the total weight of the transmitter and epoxy putty did not exceed 5% of the turtle's total body weight to avoid disruption of behaviors and movements. The epoxy putty and transmitter were camouflaged with black marker. Once the epoxy was hardened to the touch, the radio transmitter was checked to ensure proper functioning and then the turtle was released at the capture site. Prior to overwintering, the tagged turtles were relocated at last once per weak throughout the entire active season of 2017. Turtles were tracked on five occasions throughout the 2017/18 inactive season (October 18th, November 14th, December 4th, January 15th and March 14th). When each turtle was relocated, we recorded the GPS location, the habitat type and corresponding meteorological information. All relocations were mapped in ArcGIS 10.5. We determined habitat use by calculating the percentage of overwintering relocations recorded on each habitat type (Ecological Land Classification for Southern Ontario system) (Table 3).

To identify trends in overwintering water temperatures, we installed temperature loggers (HOBO Onset, Bourne, MA, USA) at 12 sites to monitor water temperature at potential overwintering sites. Habitats that were used by tagged turtles were designated confirmed habitat, while all others were considered unconfirmed. Loggers were arbitrarily placed within each major habitat type and set to record the water temperature every 4 h. We mounted the loggers to bamboo sticks or metal rebar poles approximately 7 cm above the substrate to

Table 3 Overwintering habitat types based on the Ecological Land Classification for Southern Ontario, which based on literature are considered to be overwintering habitat for snapping turtles

Habitat	Description
Flooded forest	Deciduous or coniferous trees, with standing water present
Waters edge	Habitat adjacent to a body of water, can include fallen logs and/or trees
Creek	Streams or creeks that flow throughout the year
Flooded cattails	Homogenous growth of dense cattail stands in marsh
Flooded grass	Homogenous growth of dense grass stands in marsh

approximate the location of an overwintering turtle (Edge et al. 2009). Finally, air temperature data were gathered from the McMaster University Weather Station, located within 1500 m of the study site.

The boundaries of the pre-overwintering, overwintering and post-overwintering periods were statistically determined with a break point analysis in R 3.3.2. We examined differences in onset date, overwintering duration and calculated mean water temperatures during the overwintering period for all sites. Onset date was defined as the first break point indicating a stability in water temperatures (Fig. 2a). An earlier onset date would provide earlier protection from fluctuating air temperatures and could increase changes to survival. Overwintering duration is the period between the first and second breaking point identified in the breakpoint analysis, where water temperatures remain low and stable throughout the winter and the slope is flatter (Fig. 2a). We also determined the number of days spent below −0.6 °C, the freezing temperature of turtle body fluids (Costanzo et al. 2006). We compared differences in water temperatures, onset date, duration and days spent below below −0.6 °C, between confirmed and unconfirmed sites using Student's t tests ($\alpha = 0.05$ for all statistical tests).

Results

Nesting habitat

Between 1934 and 2010, the total amount of potential nesting habitat in Cootes Paradise Marsh (CPM) decreased steadily from 270 to 140 ha, a drop of nearly 50% (Fig. 3a). Some of this decline may be attributed to higher marsh water levels as a result of Lake Ontario regulations that reduced the amount of shoreline, wet meadow and emergent marshes after the early 1960s (Fig. 4). These water-level regulations would have had the greatest effect on near-shore habitat, including the shoreline, which did experience a decline from 2 ha to 0.6 ha.

Over this time period, the relative amount of anthropogenically maintained fields has also increased from 40 to 80% of available habitat (Fig. 3b), though this is not due to an increase in the absolute amount of maintained fields, but because of an overall decline in amount of potential nesting habitats. Natural habitats including shoreline remained relatively low at approximately 1% (2–0.4 ha) across the full study period. Agricultural landscape that once dominated the region at over 40% of available habitat (95 ha) has declined to less than 5% (3 ha) by 2010. Finally, the relative amount of natural fields and gravel have remained stable.

Change detection analyses showed a uniform and widespread change in distribution of potential nesting habitat in CPM from 1934 to 2010 (Fig. 5; Table 4). Over this period, about 95 ha of the nesting habitat remained unchanged, while 176 ha had been lost and only 48 ha had been gained. Though the habitat loss was quite evenly distributed throughout the landscape, some areas experienced a larger decline than others. For example, greater habitat loss was associated with the urbanization of Dundas to the west and Westdale Village (Hamilton) to the southeast. Additionally, agricultural lands that once existed to the north of the marsh had been renaturalized to mixed wood forests in recent decades, and the increased shading from vegetation likely make it less suitable as nesting habitat. Overall, 27 ha of agricultural land have been converted to anthropogenically maintained fields, 5 ha to natural fields, and 59 ha have been lost. Additionally, 46 ha of natural fields and 68 ha of anthropogenically maintained fields have been lost. The most widespread increase was in anthropogenically maintained fields (35 ha), followed by natural fields (10 ha), with > three ha in all other classes.

The most prevalent potential nesting habitat type within our nesting survey route was anthropogenically maintained fields (87%) (Table 5), while gravel was the next most available habitat type (11%), followed by natural fields (5%), shoreline (0.7%) and created mounds (0.3%). The results of the Chi-squared test for given probabilities were significant and therefore nesting habitat use was not random ($P = <0.001^*$). Almost 50% of the 84 nesting observations made between May 23rd to July 4th ($n = 41$) occurred on created nesting mounds. Use on gravel accounted for >35% while those on shoreline habitat and anthropogenically maintained fields accounted for <10%. We consistently found more nests ($n = 71$) on anthropogenically modified areas (including created l nesting mounds and gravel shoulders of roads) than on naturally occurring nesting habitats. The large number of nesting observations combined with the relatively small area of nesting mounds resulted in a high density of nesting observations. There was a significant difference ($P = <0.001^*$) between the distances to next nearest pointe across our nesting observations and random points. Density of nesting observations was 2.9 nests per hectare.

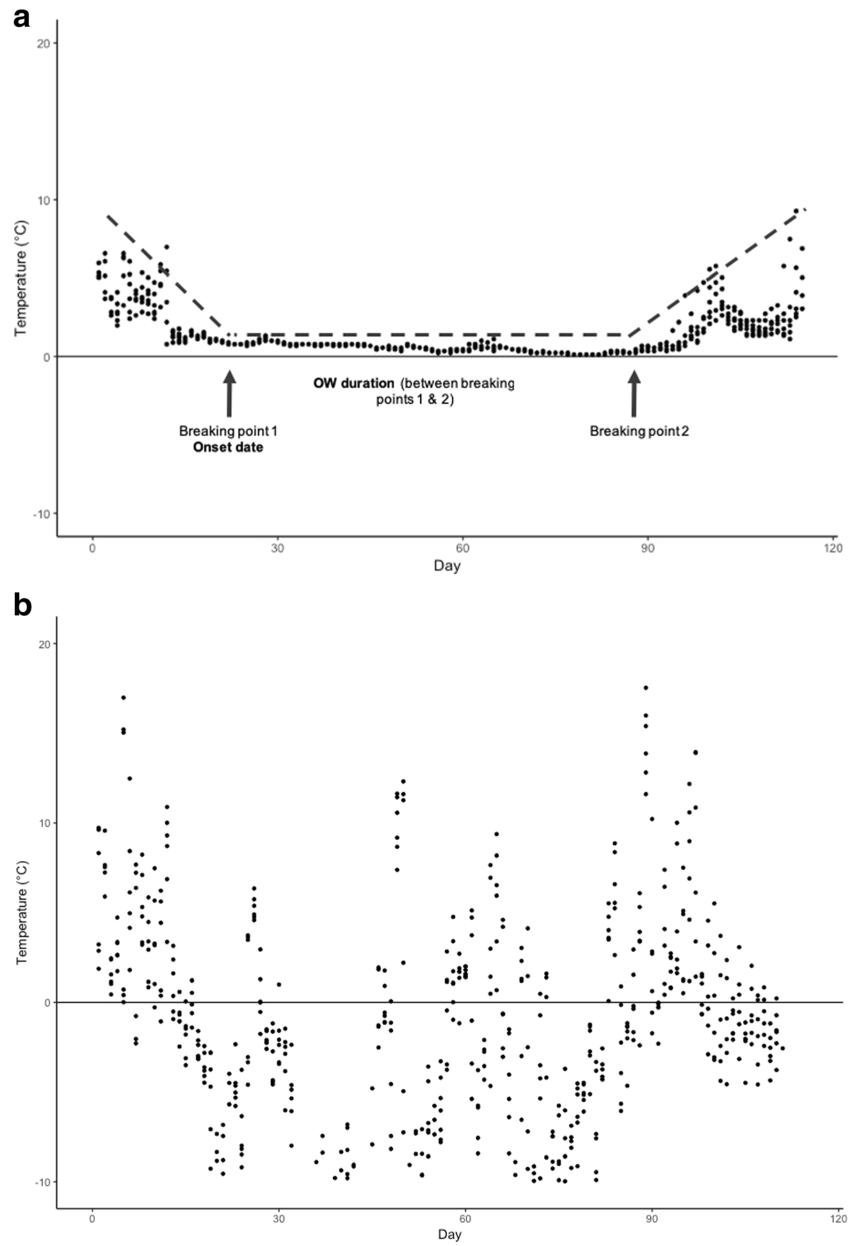


Fig. 2 Diagram of breakpoint analysis (**a**) completed on water temperatures. Onset date was defined as the first breaking point and overwintering (OW) duration is the total length of times between breaking points one and two. Variation in air temperature (**b**) from October 27th 2017 to March 30th 2018 in CPM

Overwintering habitat

In general, movement activity decreased for all tagged snapping turtles after late September, as they migrated to overwintering locations. Three of the individuals chose overwintering sites located on opposite sides of Olympic Drive or Cootes Drive (see Fig. 1) than where they had been found during the active season, and we infer from this that they crossed the road at least once. They overwintered in a wide range of upland terrestrial habitat including creeks (n = 1), flooded cattails (n = 1), flooded grass (n = 2), flooded forest (n = 3) and water's edge (n = 4) (Fig. 6). Tagged turtles used near-shore habitats rather than open-water areas, such as the middle of ponds or creeks. The maximum depth of overwintering sites (combined mud and water) was <1 m (mean of 0.57 m). Most of the turtles (n = 8/11) overwintered in areas associated with wood structures such as roots or fallen logs. Those that did not overwinter in wood structures were found in dense emergent vegetation including grasses and cattail stands.

All habitat types were used by both sexes, except that females did not use flooded grass, while males did not use flooded cattails (but they were in close proximity). There were two pairs (two males in one and one of each sex in the other) that overwintered together, with <10 m between individuals. We detected very little monthly movement during the winter, with only two individuals moving in March, one of them only 3 m and the other 30 m. All tagged snapping turtles survived

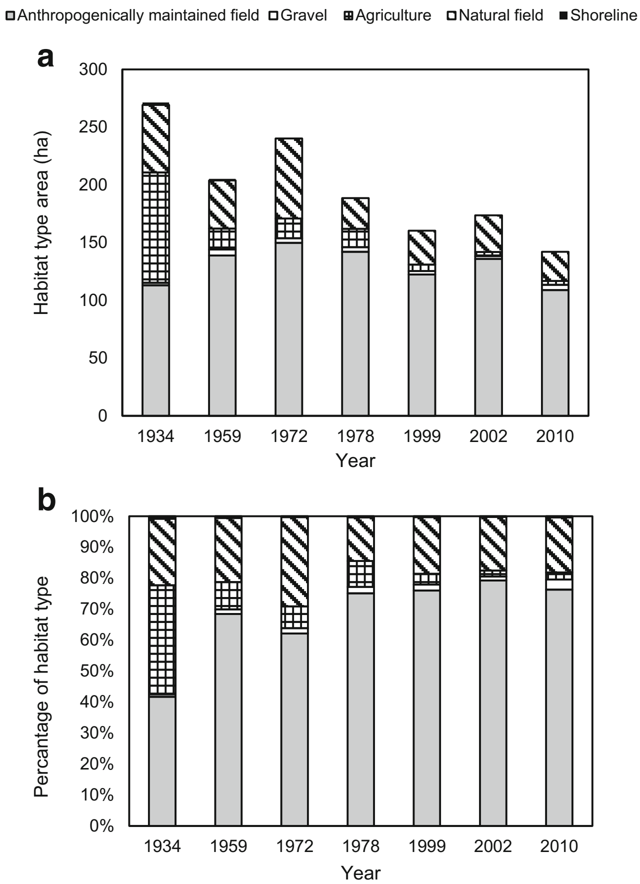


Fig. 3 Change in area of potential nesting habitat in CPM presented as (**a**) absolute amount of habitat types (ha) and (**b**) relative amount of habitat types (%)

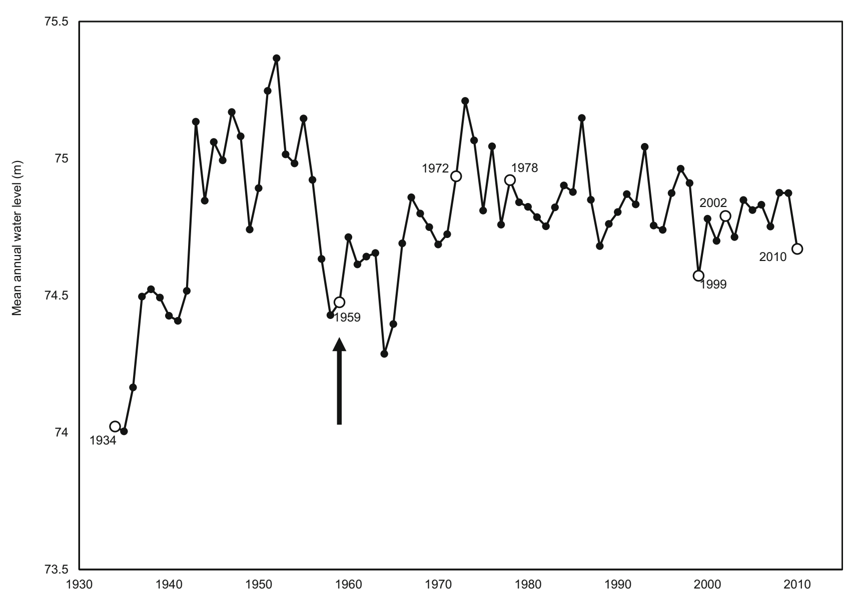
the winter. Activity increased from mid-March onward as turtles started to move throughout the wetland complex.

We analyzed the thermal data according to confirmed sites (where tagged turtles overwintered) and unconfirmed sites (where no known turtle had overwintered) (Fig. 6). Despite fluctuating and cold air temperatures (Fig. 2b), both confirmed and unconfirmed sites provided a mean water temperature during the overwintering period of 0.4 °C (P = >0.51). Despite this similarity, we noted four differences in other thermal parameters. First, the onset date for the overwintering period occurred slightly earlier for the confirmed than unconfirmed sites (December 13th vs December 16th) (P = >0.32) (Table 6). Secondly, duration of the overwintering period was longer by almost one full week for the confirmed vs unconfirmed sites (103.7 days vs 97.5 days, respectively), but not statistically significant (P = >0.51). Thirdly, the number of days below −0.6 °C (the freezing point of turtle body fluids) (Costanzo et al. 2006) was 3.3 for confirmed and 5.0 days for the unconfirmed sites, which was also not significant (P = >0.76). Finally, confirmed sites provided more stable water temperatures compared to unconfirmed sites, as indicated by the larger fluctuations and range in water temperatures for the latter.

Discussion

Common snapping turtle populations, particularly those in urban environments, face many threats, including reduced quantity and quality of critical overwintering and nesting habitat. Populations of snapping turtles that occur at the northern periphery of their home range may be at greater risk of being extirpated because of environmental change (Lesbarrères et al. 2014). It is imperative that we conserve and protect such

Fig. 4 Change in Lake Ontario mean annual water level (above sea level), arrow shows year of Lake Ontario water level regulation implementation (1963) and open circles show years where aerial photography was available



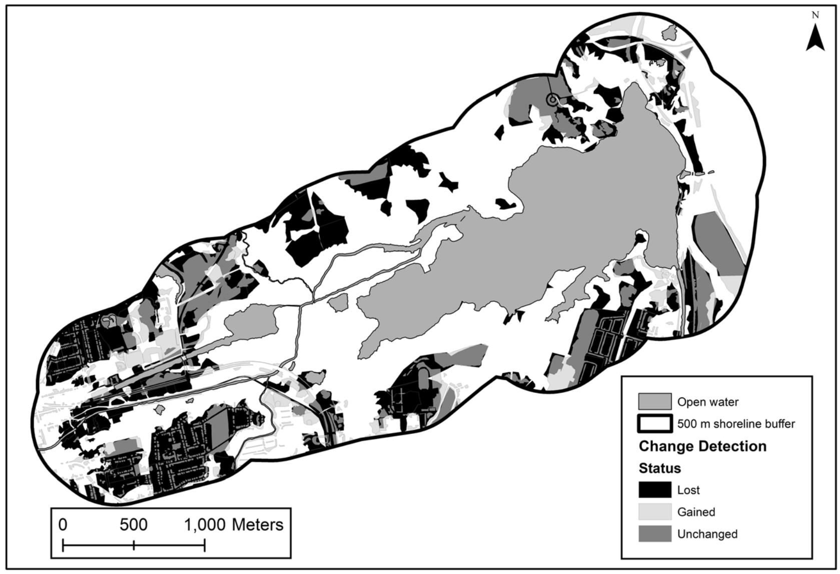


Fig. 5 Results of a change detection analysis showing changes in the amount of potential nesting habitat in CPM between1934 and 2010

isolated populations because recolonization in altered environments is difficult (Marchand and Litvaitis 2003).

Based on digital orthophotos, we determined that the amount of potential nesting habitat in Cootes Paradise Marsh (CPM) has declined by almost half between 1934 and 2010. Turtles are disproportionately using created gravel mounds for nesting rather than naturally occurring habitats, which are limited. Both sexes overwintered in a wide range of upland habitat types. There were some minor differences in water characteristics between confirmed and unconfirmed sites; however, they were not statistically significant. Specifically, confirmed sites provided an earlier onset of the overwintering duration (hence a longer overwintering period), a narrower range in temperatures and lower fluctuations around a mean of 0.4 °C, and a fewer number of days below the critical freezing temperature of −0.6 °C. Therefore, confirmed sites may provide a slightly longer, more stable thermal environment that protected snapping turtles from freezing during the winter. Overwintering sites within CPM may not be limiting due to the wide range of habitat types used and minor differences in water temperature characteristics between confirmed and unconfirmed sites.

Consistent with other studies that examined changes in wetland habitat in southern Ontario (Markle et al. 2018; Wilcox et al. 2008), we found long-term changes in habitat composition in this highly urbanized ecosystem, changes that may have drastically reduced the availability of potential nesting habitat for the once abundant snapping turtle population in CPM (COSEWIC 2008; Galbraith et al. 1988). One of the main changes in potential nesting habitat is related to conversion of agricultural fields to anthropogenically maintained fields (i.e. lawns), which now represent almost 80% of available potential nesting habitat. Presence of grass can alter the temperature and moisture content of the substrate, rendering the habitat less suitable for successful egg incubation and hatchling emergence (Bobyn and Brooks 1993; Kolbe and Janzen 2002). Additionally, activities associated with anthropogenically maintained fields, such as mowing (Thompson et al. 2017) and pesticide use (de Solla et al. 2011) could also result in decreased nest success. Even though agricultural fields currently represent a small portion of available potential nesting habitat, they are attractive to female snapping turtles (Thompson et al. 2017); however, these are also suboptimal habitats because incubation temperatures are

Table 4 Results from the change detection analysis: change in habitat types from 1934 to 2010 including each type of habitat lost or gained

	Habitat type					
	Anthropogenically maintained field	Gravel	Agriculture	Natural field	Shoreline	Total
Habitat lost from 1934 (ha)	67.85	1.43	59.35	45.90	1.78	176.31
Habitat gained in 2010 (ha)	34.81	2.33	0.03	10.26	0.29	47.72

Table 5 Proportion of potential nesting habitat surveyed versus nesting observations

Habitat type	Survey area proportion (%)	Nesting observations (%)
Natural field	1.0	0.1
Anthropogenically maintained field	87.0	8.3
Shoreline	0.7	7.1
Created mound	0.3	48.8
Gravel	11.0	35.7

lower (Freedberg et al. 2011) and hatchlings can become spatially disoriented when they emerge (Pappas et al. 2013; Congdon et al. 2015).

The almost 50% decline in potential suitable nesting habitat from 1934 to 2010 could have led to reduced recruitment and a subsequent decrease in population size. The change detection showed that higher loss of potential nesting habitat occurred near Dundas and Westdale, two urbanized areas, which are commonly associated with meso-predators (Riley and Litzgus 2014; Thompson et al. 2017; Urbanek et al. 2016) including raccoons, skunks and foxes. High nest depredation can lower recruitment, which can eventually lead to aging populations and population decline (Browne and Hecnar 2007; Markle et al. 2018). Additionally, Thompson et al. (2017) noted that reproductive success of snapping turtles is lowered in polluted and/or modified environments.

The disproportionate use of created mounds and high density (compared to random points) in this study suggest that there may be a shortage of suitable nesting habitat in the ecosystem (Loncke and Obbard 1977). On the one hand, studies have found that nesting in created mounds can lead to increased hatching and nest success compared with roadsides (Paterson et al. 2013). On the other hand, high densities of nests can facilitate increased rates of nest depredation (Dekker 2015), which can be as high as 100% for snapping turtle nests in natural ecosystems (Linck et al. 1989; Marchand and Litvaitis 2003). Therefore, it is important to have a sufficient number of created mounds installed to facilitate nest success, in order to minimize risk of depredation from meso-predators in such an urbanized environment.

Snapping turtles overwinter in a wide range of aquatic habitats, including shallow streams/creeks (Brown and Brooks 1994; Ultsch and Lee 1983), edge of the water body or stream (Obbard and Brooks 1981), muddy bottoms of marshes, ponds and lakes (Fitch 1956; Obbard and Brooks 1981), muskrat houses (Carr 1952; Ernst and Lovich 2009), terrestrial woodlots (Ryan et al. 2014) and even beaver structures (Strain et al. 2012). Tagged snapping turtles used flooded grass, flooded cattails, waters edge, creeks and flooded forest and all survived the winter, suggesting that these sites are suitable and therefore important to population persistence.

We also found that tagged snapping turtles used shallow sites (< 1 m in maximum depth) that were associated with woody structures such as fallen logs or roots (Meeks and

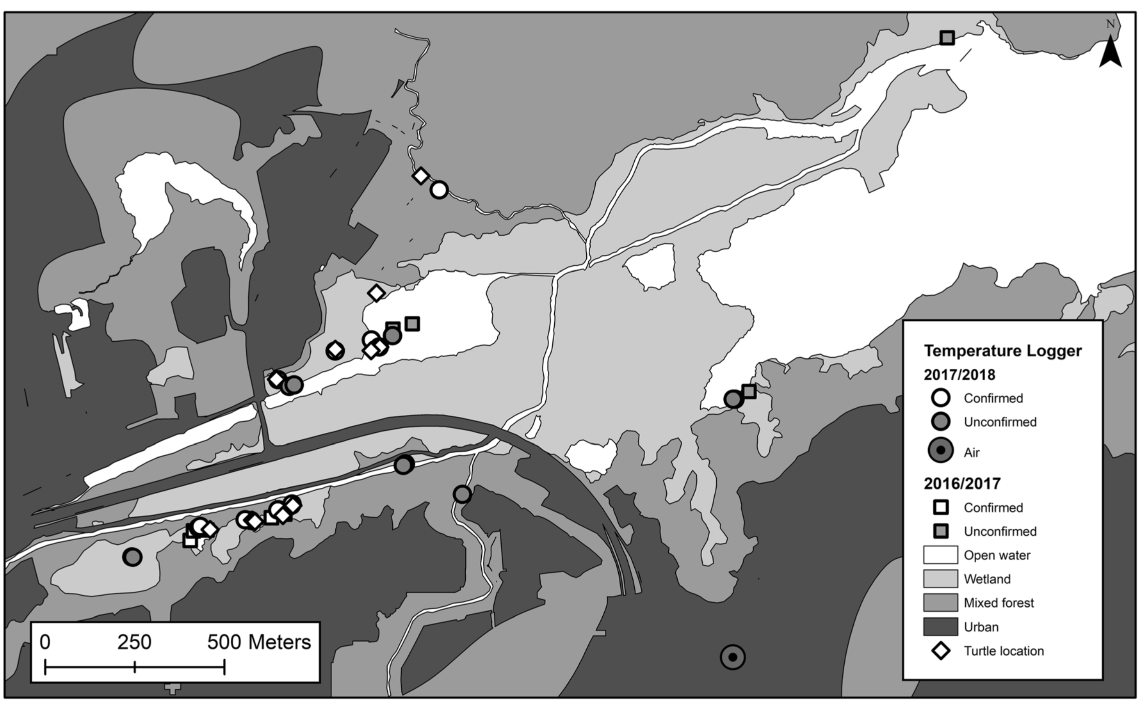
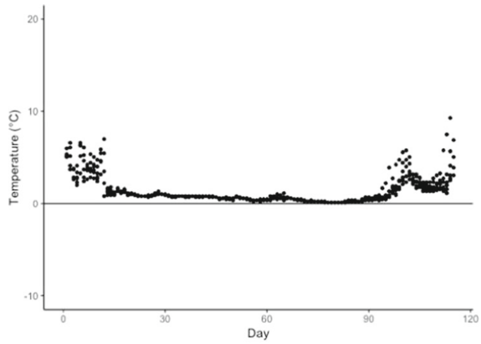
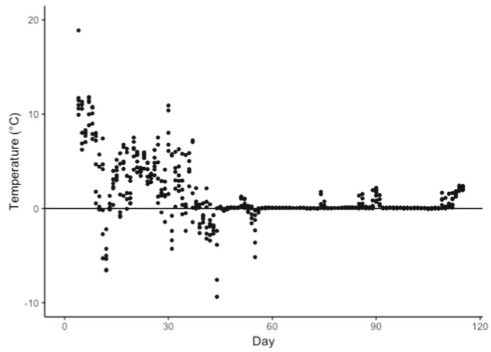


Fig. 6 Location of temperature loggers in wetland habitat during October 2016 to March 2017, October 2017 to March 2018 and location of tagged snapping turtles between October 2017 to March 2018

Table 6 Comparison of water temperatures during the winters of 2016/2017 and 2017/2018, for sites where tagged turtles had been present during the winter (Confirmed = Y), and where they had not (Confirmed = N). A representative plot of temperatures for each site type is shown, along with the mean date of onset of low temperatures, mean overwintering duration, mean water temperature during the period of low temperatures, and the mean number of days in which temperatures were below 0.6 °C (mean days below). No means were significantly different

Confirmed	Representative water temperature graph	Mean onset date	Mean OW duration	Mean temp (°C)	Mean days below
Y		Dec 13th	103.7	0.44	3.3
N		Dec 16th	97.5	0.44	5.0

Ultsch 1990; Pettit et al. 1995; Ultsch 2006). Woody structures may help to conceal them from predators and therefore enhance survivorship. Removal of such structures (even if they are in protected areas such as conservation areas or parks) could leave turtles vulnerable to mammalian predation and contribute to population decline. Future studies could examine additional specific physical characteristics of overwintering sites, including various types of concealment, depth of water/mud or amount of ice coverage. Such information would be beneficial for management of habitats undergoing change related to global climate change or for creation/restoration of overwintering sites for introduced individuals.

Based on our observations, protecting the upland matrix of CPM will ensure that suitable overwintering habitat will be available for the population of snapping turtles. Others (i.e. Buhlmann and Gibbons 2001; Pettit et al. 1995) have also suggested that protecting the upland matrix was crucial to promoting winter survival of snapping turtles and ultimately population persistence. Two groups of snapping turtles overwintered together, perhaps because of limited suitable sites (Markle and Chow-Fraser 2017).

Both confirmed and unconfirmed overwintering sites shared the same mean water temperature (0.4 °C), which is colder than that determined for a population of snapping turtles in Algonquin Provincial Park (1.0–1.7 °C; Brown and Brooks 1994). Paterson et al. (2012) found the mean body temperature of snapping turtles in Algonquin Park was 1.29 °C, while the mean water temperature was 2.59 °C. Turtles must select sites with water temperatures that keep them from freezing, but that also sufficiently cool to lower their metabolism and thus conserve energy (Edge et al.

2009; Markle and Chow-Fraser 2017). In our study, they appear to be using sites that provide slightly colder mean water temperatures than in previous studies (see Brown and Brooks 1994; Paterson et al. 2012).

All of the tagged snapping turtles overwintered in varying depths of mud, with a layer of water on top of the substrate. It is possible that snapping turtles in our study made use of the mud for thermal purposes but were also physically close to water to acquire the DO. Site selection and thermal suitability likely contributed to the survival of all 11 tagged snapping turtles through the winter. Suitable overwintering sites contribute to adult survival, which is crucial to population maintenance since snapping turtle populations do not have density dependent responses (Brooks et al. 1991; Congdon et al. 1994) and are unable to compensate for chronic loss of breeding adults (Aresco and Gunzberger 2007).

Effective management of at-risk species requires a thorough understanding of threats at all life stages from egg to adult (Marchand and Litvaitis 2003). Almost all previous information on snapping turtles are for populations living in relatively undisturbed habitats. This is the first study of a highly urbanized population in Canada, that has experienced a dramatic loss in amount of critical habitat by almost 50% in previous decades, which is well within the life time of such long-lived turtles. This loss of potential nesting habitat could be reducing recruitment and ultimately contributing to population decline. Our survey of nesting activities suggests that there is currently a lack of suitable nesting sites within CPM, and that additional created nest sites should be installed as soon as possible, to decrease nest density and thus lowering depredation rates. There is no indication that availability of overwintering sites is limited, but we recommend that the upland matrix surrounding the western end of CPM be protected from further alterations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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