



City dwellers: habitat connectivity and demographic responses of a semi-aquatic turtle in Australia

Bruno de Oliveira Ferronato^{1,2} · Anke Maria Hoefler³ · Isobel Booksmythe⁴ · Rod Ubrihien⁵ · Arthur Georges¹

Accepted: 18 July 2024

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2024

Abstract

Urbanization and fragmentation of habitat are major drivers of population declines in wildlife in cities. This study evaluated fragmentation of aquatic systems in the context of urbanization, using the Eastern long-necked turtle *Chelodina longicollis* as a model as it is a generalist species, highly vagile and engages in regular overland migration. During two seasons (2020–22), we compared *C. longicollis* demography in stormwater ponds in two distinct urban drainages, one with greater habitat connectivity (lower road network and an unmodified creek) and one with lower habitat connectivity (higher road network and stormwater drains) in Canberra, south-eastern Australia. Most of the parameters related to habitat (pond age and size) and food requirements (phosphate and prey biomass) for *C. longicollis* were similar between the two drainages, in addition to proportion of females, overall size-frequency distributions and population size (corrected for variation in capture probability). However, there was a significant effect of the interaction between pond habitat connectivity and pond size with population sizes increasing more steeply in higher than in lower connectivity sites ($F_{1,4} = 14.3, p = 0.02$). We also recaptured a marked turtle from a previous study in the drainage with more habitat connectivity, 14 years later and 15 km from its initial point of capture. This demonstrates the ability of the species to move within an urbanized context. Despite evidence of *C. longicollis* being resilient to urbanization, dispersal constraints seem to affect population dynamics and long term population viability in areas with low habitat connectivity.

Keywords Urbanization · Landscape connectivity · Habitat fragmentation · Freshwater turtles · Population · Movement

Introduction

Landscape-scale habitat connectivity plays a major role in sustaining viable metapopulations of wildlife, facilitating movement of organisms, increasing gene flow, and increasing resilience to stressors (Brodie et al. 2016; Watson et al. 2017). Much of the research on fragmentation, restoration and connectivity come from studies on terrestrial and forest ecosystems (Brodie et al. 2016; Santo-Silva et al. 2016; Ma et al. 2023), but there is a growing number of investigations on these topics in aquatic systems (Fuller et al. 2015; Gido et al. 2015; Birnie-Gauvin et al. 2020). Damming of rivers, road crossings and diversion structures are some of the man-made barriers that affect habitat connectivity in large rivers and streams (Fuller et al. 2015; Gido et al. 2015). Additionally, fragmentation of terrestrial linkages between aquatic habitats may affect vertebrates that use both terrestrial and aquatic systems and negatively impact their distribution and population parameters (Cushman 2006; Isdell et al. 2015).

✉ Bruno de Oliveira Ferronato
brunoferronato@hotmail.com

¹ Institute for Applied Ecology, University of Canberra, Bruce, ACT 2601, Australia

² Ginninderra Catchment Group, 21 Bingle Street, Flynn, Australian Capital Territory 2615, Australia

³ FrogWatch Program, Ginninderra Catchment Group, 21 Bingle Street, Flynn, Canberra, Australian Capital Territory 2615, Australia

⁴ Office of Water, Environment, Planning and Sustainable Development Directorate, ACT Government, Canberra 2601, Australia

⁵ Centre for Applied Water Science, University of Canberra, Bruce ACT 2601, Australia

Urbanization and its resulting population sprawl are major contributors to fragmentation of habitat worldwide (Riley et al. 2003; Liu et al. 2016). Urbanization affects both terrestrial and aquatic systems, through land conversion, increase in impervious surfaces and road network, and river channel change (Galster et al. 2008; Liu et al. 2016; Moll et al. 2019). Urbanization and fragmentation are drivers of population decline in vertebrates inhabiting cities (Riley et al. 2003; Xu et al. 2018; Habrich et al. 2021), though there are a number of urban ‘adapters’ and ‘exploiters’ (e.g. starlings, house sparrows, raccoons) which benefit from the increased food availability in urban areas (McKinney 2002; Bateman and Fleming 2012). Fragmentation in urban areas affect animals at the landscape scale, and studies have demonstrated that large fragments with diverse habitat types support the highest species richness within an urban context (Johnson and Karels 2016; Delaney et al. 2021). Additionally, habitat connectivity in urban areas plays a major role for animal movement, survival and persistence (FitzGibbon et al. 2007; Braaker et al. 2014; Kang et al. 2015).

Fragmentation of habitat poses a significant threat to several freshwater turtle species throughout the world (Rizkalla and Swihart 2006; Serrano et al. 2020; Luiselli et al. 2021; Bárcenas-García et al. 2022). With urbanization expansion and encroachment of natural habitats on the rise (Li et al. 2022; Simkin et al. 2022), understanding how turtle species respond to such threats are essential to mitigate and manage urban populations (Gibbs and Steen 2005; Rees et al. 2009; Ferronato et al. 2017). The response of freshwater turtles to urbanization varies. Some species perish owing to habitat loss or modification (e.g. Western swamp turtle *Pseudemys umbrina* Kuchling 2000; Eastern mud turtles *Kinosternon subrubrum* Eskew et al. 2010). Others are tolerant of pollution and benefit from food availability in urban areas (e.g. Geoffroy’s side-necked turtle *Phrynops geoffroanus* Souza and Abe 2000; Stripe-necked terrapin *Mauremys leprosa* Hassani et al. 2019) and active immune system (*P. geoffroanus* Ferronato et al. 2009). Road mortalities can still pose a risk to otherwise well adapted species (Gibbs and Steen 2005; Langen et al. 2012; Santori et al. 2018).

The Eastern long-necked turtle (*Chelodina longicollis*) has the largest distribution of Australian freshwater turtles, ranging from Queensland in the north to Victoria in the south, inhabiting rivers, farm dams, billabongs, and urban ponds (Kennett et al. 2009; Rees et al. 2009; Stokeld et al. 2014). It is a generalist species that is well adapted to flood-drought cycles, owing to its ability to navigate on land and colonise new wetlands (Roe and Georges 2008; Kennett et al. 2009). During terrestrial migrations, it is reported to rely on visual and olfactory cues (Graham et al. 1996) and can cover distances greater than 5 km (Kennett et al. 2009; Roe et al. 2009). Additionally, it has a low rate of desiccation

(Chessman 1984a), and can aestivate under the leaf litter for more than a year during droughts (Roe and Georges 2007).

Chelodina longicollis seem resilient to urbanization (Burgin and Ryan 2008; Rees et al. 2009; Stokeld et al. 2014), with some urban populations being more abundant and growing faster than natural counterparts (Roe et al. 2011). However, road mortality is one of the main threats to *C. longicollis* (Ferronato et al. 2016; Santori et al. 2018), and road network densification is a key component of increasing urbanization. While previous studies have shown that wildlife decrease in diversity and abundance with increasing urbanization (Johnson and Karels 2016; Delaney et al. 2021), to date, little is known about how the extent of urban habitat connectivity, or lack of it, influence demographic responses in *C. longicollis*. In this study we aimed to evaluate how the extent of urbanization and its effect on habitat connectivity affect *C. longicollis* demography by studying two distinct drainages explicitly differing in their road network densities (one peri-urban, with greater connectivity, and one urban, with lower connectivity) in Australia.

Materials and methods

Study area

From September 2020 to March 2022, we studied *C. longicollis* populations in two distinct drainages in Canberra, in the Australian Capital Territory (ACT), south-eastern Australia. One was part of the Sullivans Creek drainage, which is considered a highly developed area with less habitat connectivity (Figs. 1 and 2). We sampled turtles in four stormwater ponds in the lower section of the drainage, within the suburbs of Dickson, Lyneham and O’Connor. Sampling sites were Dickson wetland (pond age: 12 years since construction, pond size: 8105 m²), Lyneham wetland (age: 10 y, size: 12,046 m²), David Street wetland (age: 21 y, size: 1274 m²), and Banksia St. wetland (age: 12 y, size: 1115 m²). Sullivans Creek and its tributaries in this part of the drainage are not natural and are composed of a series of concrete drains and channels (Figs. 1 and 2). The Inner North cluster in this study is considered to have low habitat connectivity for turtles owing to the dense road network along the drainage (see Anthropogenic impact), potential for road mortalities (Santori et al. 2018), and the presence of stormwater drains, which are only hydrologically connected after heavy rain.

We also sampled turtles in four stormwater ponds in the lower section of the Ginninderra Creek drainage, which is considered peri-urban, with more habitat connectivity and less development, where the creek and its tributaries are unmodified (Figs. 1 and 3). This area is known as West

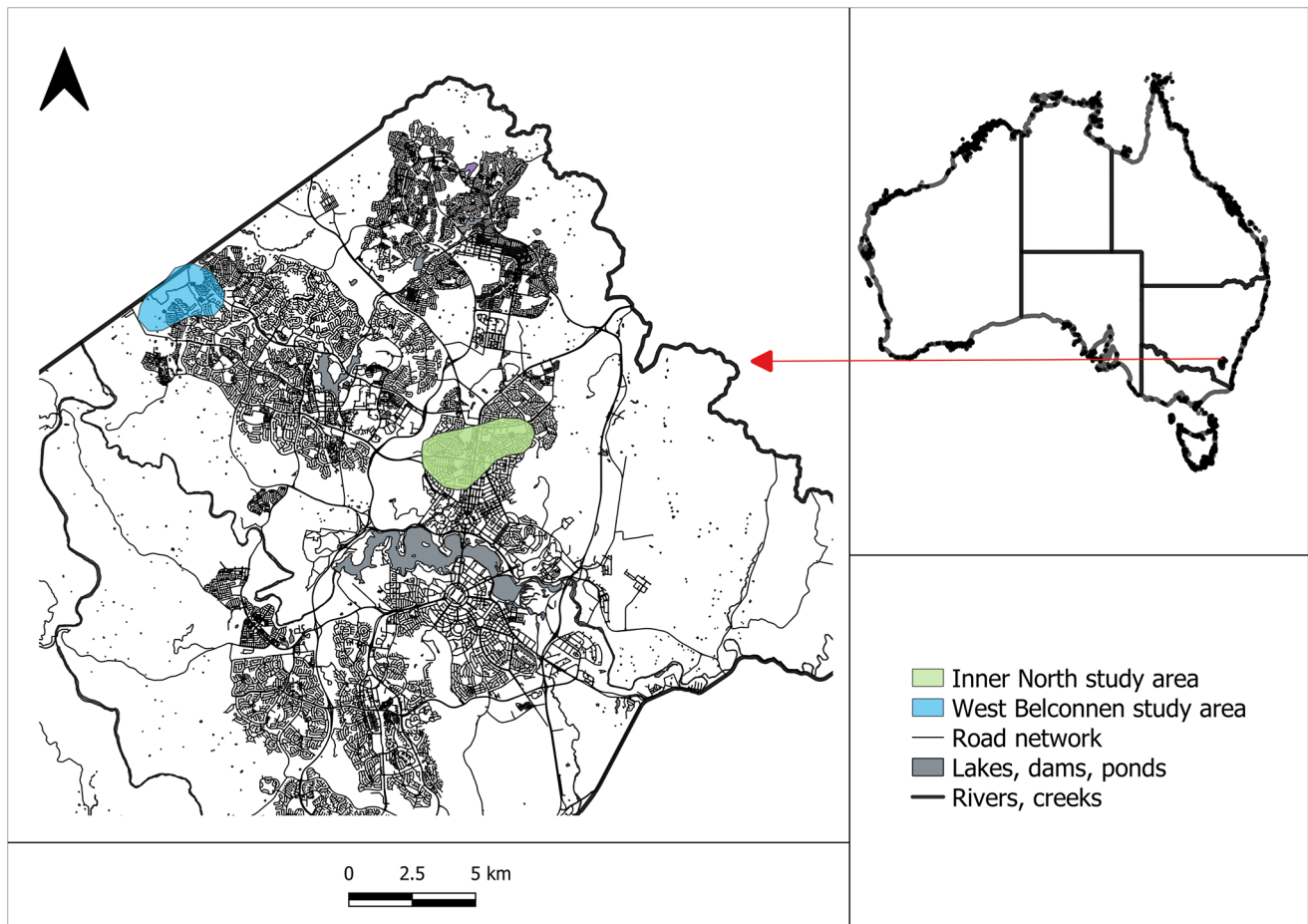


Fig. 1 Study areas, highlighting lower Sullivans Creek drainage (Inner North) and lower Ginninderra Creek drainage (West Belconnen), Canberra, Australian Capital Territory, Australia

Belconnen. The sampling sites were Jarramlee pond (age: 28 y, size: 5855 m²), Fassifern pond (age: 28 y, size: 5413 m²), Refshauge Crescent pond (age: 9 y, size: 2026 m²), and Hollows Circuit pond (age: 8 y, size: 2375 m²) situated in the suburbs of Dunlop and Macgregor. The West Belconnen cluster in the present study has greater habitat connectivity for turtles as there are few roads between the ponds and the creek is unmodified.

Climate

The climate in the ACT is temperate, with mean annual rainfall of 633 mm (1961–1990, Australian Bureau of Meteorology 2023). Rainfall in Australia is highly variable and is influenced by phenomena like El Niño, La Niña and the Indian Ocean Dipole, being mainly dry with occasional periods of elevated rainfall. The last severe droughts occurred from 2001 to 2009 (van Dijk et al. 2013) and 2017–2019 (Nguyen et al. 2021). During the study period, we had a period of elevated rainfall (2020: 790 mm, 2021: 912 mm, 2022: 892 mm, Canberra Airport weather station, Australian

Bureau of Meteorology 2023), influenced by La Niña and a negative Indian Ocean Dipole (Bureau of Meteorology 2022).

Turtle sampling

Freshwater turtles were captured using cathedral traps baited with sardines. Sampling occurred once per month at all ponds in each drainage from September 2020 to March 2022, except from April to August as turtles are inactive during these colder months, with a total of 14 sampling occasions per site. Four traps per stormwater pond were set in the morning and removed in the afternoon (after approximately four hours), with the order of ponds randomly selected on each sampling occasion. Captured turtles were marked with shell notching for future identification, and we measured straight-line carapace length (CL), carapace width (CW), plastron length (PL) and plastron width (PW) with callipers (± 0.1 mm), and body mass with a scale (± 5 g). Turtles were sexed based on external morphological features (Kennett and Georges 1990), and considered



Fig. 2 Sullivans Creek drainage (stormwater drain) and four stormwater ponds sampled (Inner North), Canberra, Australian Capital Territory, Australia

juveniles if $CL < 145$ mm and adults if $CL > 145$ mm. They were released at their point of capture.

Productivity and pond age and size

We estimated primary productivity by measuring phosphate (P) and nitrates (N) from water samples in each stormwater pond. We used phosphate and nitrate kits (Macherey-Nagel Viscolor HE Low Phosphate kit 0.01-0.25 mg/L and Macherey-Nagel Visicolor ECO Nitrate kit 1-120 mg/L, respectively), following the methodology of the Upper Murrumbidgee Waterwatch Program (<https://www.act.waterwatch.org.au/resources/volunteer-resources>). We estimated secondary productivity as the standing-crop biomass of potential *C. longicollis* prey items (Chessman et al. 1984b; Georges et al. 1986) in each stormwater pond. We conducted four time-constrained (30 s) searches in the littoral zone of each pond using a 34 cm x 28 cm dipnet (250 μ m mesh; Roe et al. 2011). Samples were preserved in 90% ethanol and later sorted in the lab. Prey items were dried on absorbent paper for 10 min before weighing (± 0.01 g)

(Roe et al. 2011). Both primary and secondary productivity measurements were taken in December 2020 and March 2021. For each pond, we calculated the mean of the two P and N (primary productivity), and prey biomass measurements (secondary productivity). We confirmed equal sample variances with Levene's test, and used two-sample t-tests to compare mean P, N and prey biomass among low- and high-connectivity sites. T-tests were also used to compare the average age and size of the wetland sites in each drainage. Analyses were performed in R version 4.1.3.

Anthropogenic impact

Anthropogenic impact was measured by calculating road density ($\text{km of road}/\text{km}^2$) within 700 m of each of the eight stormwater ponds using QGIS (Version 3.22.7). This distance was chosen based on movement distances of *C. longicollis* determined from previous studies in the region (Rees et al. 2009; Roe et al. 2009). We used a two-sample t-test to compare road density around sites in the Inner North (low

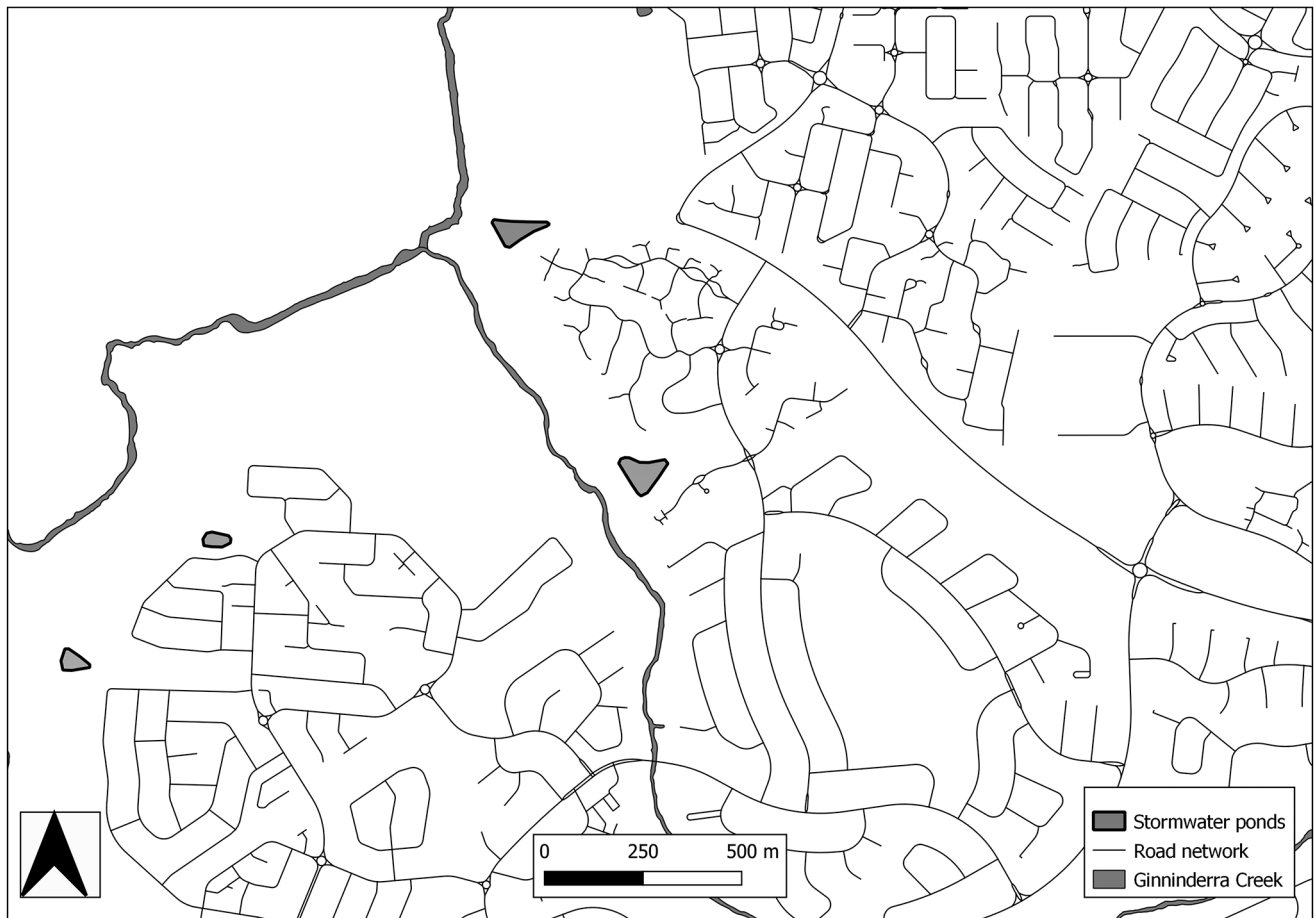


Fig. 3 Ginninderra Creek drainage (unmodified creek) and four stormwater ponds sampled (West Belconnen), Canberra, Australian Capital Territory, Australia

habitat connectivity) and West Belconnen (greater connectivity). Analyses were performed in R version 4.1.3.

Demographic parameters

We compared proportion of females, estimated population size, and size-frequency distributions between drainages. We compared the proportions of females present at low- and high-connectivity sites using a generalised linear mixed model (GLMM; function `glmer` in the package `lme4`) with binomial error structure, including pond ID as a random effect. For estimation of population size, we used the Horvitz-Thompson type estimator (Seber 1982):

$$N = \frac{n}{p}$$

where N is the estimated population size, n is the number of unique turtle captures in each pond, and p is the capture probability. Relative population sizes (corrected for variation in capture probability) were compared between drainages with

a linear model including pond size as a covariate. Size-frequency distributions for the two population clusters were compared using a chi-square test. Analyses were performed in R version 4.1.3.

Survivorship and capture probability were estimated using Cormack-Jolly-Seber (CJS) open population capture-recapture models in the program MARK. We estimated parameters among groups (adult male, adult female, and juvenile), drainages (Inner North: low habitat connectivity; and West Belconnen: greater connectivity), and over time (sampling occasions). We collapsed capture histories into two occasions of approximately equal duration per year (September to December and January to March) for analysis. We started with models where survivorship (Φ) and capture probability (p) were allowed to vary over time, among groups and among sites. We then fitted a series of reduced parameters models and ranked them based on Akaike's Information Criterion (AIC). If competing models had AIC values ≤ 2.0 , we considered them as having some support (Lebreton et al. 1992). We assessed the fully saturated model's adequacy to describe the data using a

bootstrap goodness-of-fit test with 500 simulations and an overdispersion parameter (\hat{c}) was derived by dividing the model deviance by the mean of the simulated deviances (Cooch and White 2014). If there was evidence for overdispersion ($\hat{c} > 1$), we adjusted the models with the derived \hat{c} to improve model fit and calculated a quasi-likelihood estimator, QAICc (Burnham and Anderson 1998). All parameters were estimated using model averaging.

Results

Productivity and pond age and size

The Inner North had significantly higher concentrations of N than West Belconnen ($t_{(5,3)} = 3.02$, $p = 0.03$; Table 1), but there was no difference in P ($t_{(4,2)} = 1.17$, $p = 0.30$; Table 1) or in biomass of prey ($t_{(4,9)} = 0.68$, $p = 0.53$; Table 1). There was also no difference between the drainages in site age ($t_{(4,1)} = 0.73$, $p = 0.50$) or area ($t_{(3,8)} = 0.60$, $p = 0.58$; Table 1).

Anthropogenic impact

Road density around sampled ponds ranged from 4.82 to 10.41 km/km² at the West Belconnen ponds (greater connectivity), and from 14.61 to 15.92 km/km² at the Inner North ponds (lower connectivity). The density of roads was significantly higher around ponds in the Inner North drainage (15.2 ± 0.3 km/km²) than the West Belconnen drainage (7.0 ± 1.2 km/km²; $t_{(3,3)} = 6.54$, $p = 0.005$).

Demographic parameters

We captured 46 individual turtles in Inner North and five of them were captured twice. In West Belconnen we captured 181 individual turtles, and 16 animals were captured twice. There was no difference in the proportion of females (mean, SE, n , range) between low-connectivity sites (Inner North: 0.52 ± 0.18 , $n = 4$, 0.11–1.0) and high-connectivity sites (West Belconnen: 0.46 ± 0.05 , $n = 4$, 0.41–0.61) ($z = 1.05$, $p = 0.29$).

Relative population size (corrected for variation in capture probability) increased with pond size ($F_{1,4} = 31.1$,

$p = 0.005$) and there was a significant effect of the interaction between pond habitat connectivity and pond size ($F_{1,4} = 14.3$, $p = 0.02$) with population sizes increasing more steeply in high- than in low-connectivity sites (Fig. 4). Accounting for these effects, the overall difference in population size between habitat types was not significant ($F_{1,4} = 0.01$, $p = 0.93$) (Inner North: 47.3 ± 20.9 , $n = 4$, 3.6–92.8; West Belconnen: 142.6 ± 35.8 , $n = 4$, 82.3–229.4).

The size-frequency distributions for the two population clusters were not significantly different ($\chi^2 = 16.92$, d.f. = 14, $p = 0.26$; Fig. 5). Interestingly, a male turtle captured in the present study in West Belconnen was a recapture from a previous study in the upper section of Ginninderra Creek (Roe et al. 2011). This turtle was marked in November 2006 in a farm dam at Ginninderra Experiment Station (CSIRO), with a carapace length of 203.4 mm, plastron length of 158.5 mm and mass of 860 g, and recaptured in Hollows Circuit Pond in December 2020 (CL: 204.8 mm, PL: 159.6 mm, m: 895 g), approximately 15 km downstream along the drainage from its initial point of capture.

The best supported model, according to the capture-mark-recapture analysis, had survivorship and capture probability constant over time, among groups and between sites (Table 2). Nonetheless, there was also some support for two other competing models (Δ QAICc < 2, Table 2). The second-best supported model (Δ QAICc = 1.13) had survivorship constant over time, among groups and between sites, and capture probability varying according to site, with lower capture probability for Inner North turtles (Tables 2 and 3). The third best supported model (Δ QAICc = 1.17) had survivorship varying according to site, with lower survivor for Inner North turtles (Tables 2 and 3), and capture probability constant over time, among groups and between sites.

Parameters were derived as weighted averages based on their quasi-likelihood Akaike's information criterion (QAICc) values, adjusted for model overdispersion. Results expressed in mean \pm SE. According to model selection, there's support for both Φ and ρ constant; support for Φ constant and ρ varying to site; and some support for Φ varying to site and ρ constant.

Table 1 Drainage means for primary (phosphate and nitrate) and secondary productivity (prey biomass), and pond age since construction and dimensions in stormwater ponds, inhabited by *Chelodina longicollis*, with lower habitat connectivity (Inner North) and greater connectivity (West Belconnen), Canberra, Australian Capital Territory, Australia

	P (mg/L)	N (mg/L)	Prey biomass (g)	Pond age (years)	Pond area (m ²)
Inner North ($n = 8$)	0.03 ± 0.007^A (0.01–0.07)	0.54 ± 0.04^A (0.25–1.0)	2.50 ± 0.65^A (0.69–5.09)	13.75 ± 2.46^A (10–21)	5635 ± 2687^A (1115–12,046)
West Belconnen ($n = 8$)	0.02 ± 0.003^A (0.01–0.03)	0.34 ± 0.05^B (0.0–0.75)	3.36 ± 1.08^A (0.53–6.01)	18.25 ± 5.63^A (8–28)	3917 ± 998^A (2026–5855)

Mean \pm S.E. (min – max); within columns, different superscripts indicate significant differences between low- and high-connectivity drainages

Fig. 4 Eastern long-necked turtle (*Chelodina longicollis*) population sizes increase more steeply with pond size in high-connectivity habitats (West Belconnen) than in low-connectivity habitats (Inner North). Point sizes are proportional to pond size

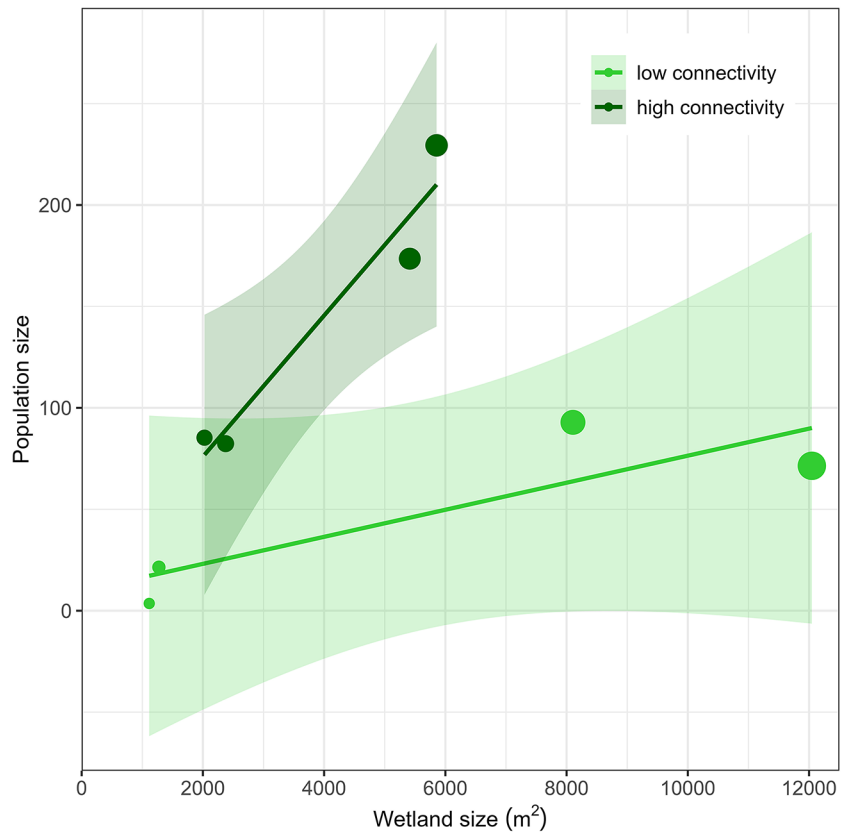


Fig. 5 Eastern long-necked turtle (*Chelodina longicollis*) size class (plastron length, mm) distributions for the Inner North (lower habitat connectivity) and West Belconnen (higher habitat connectivity) population clusters. Bars are labelled with the upper limit of each 15 mm size class (i.e. ‘45’ includes turtles between 30.1–45 mm in length). Canberra, Australian Capital Territory, Australia

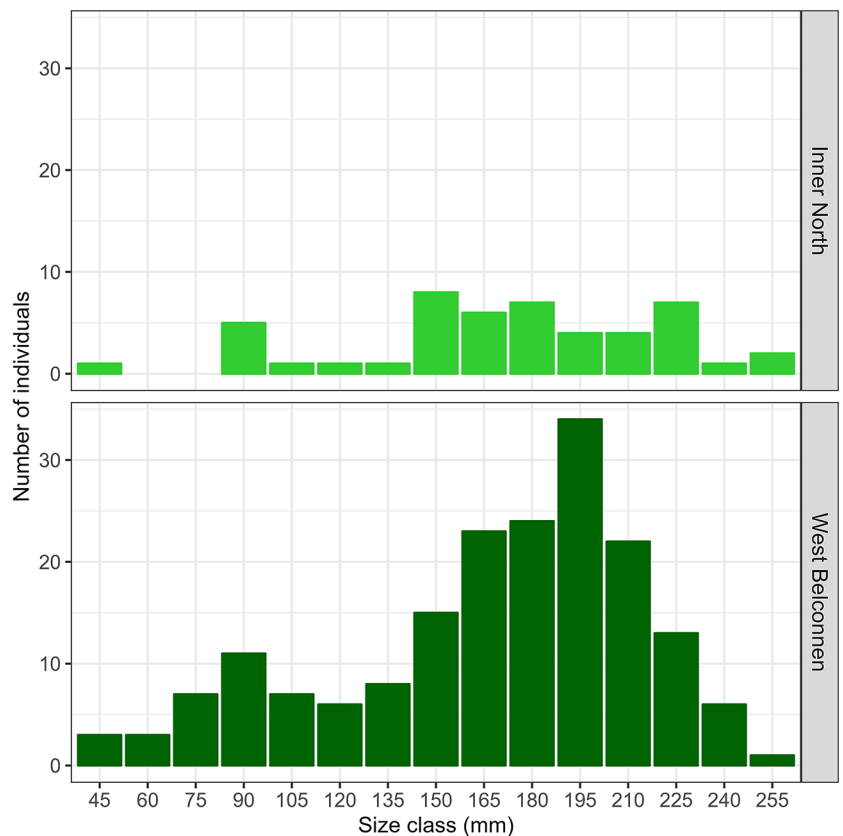


Table 2 Models of survivorship (Φ) and capture probability (ρ) of *Chelodina longicollis* among groups (adult male, adult female, and juvenile), between sites (Inner North: low habitat connectivity; and West Belconnen: greater connectivity), and over time (twice per year) in the Australian Capital Territory, Australia, 2020–2022. Models were compared and ranked with a quasi-likelihood Akaike's Information Criterion (QAICc) estimator corrected for overdispersion ($\hat{c} = 1.70$)

Model	QAICc	Δ QAICc	Weight	Parameters	Deviance
Φ (.) ρ (.)	82.9	0.00	0.40	2	18.9
Φ (.) ρ (site)	84.0	1.13	0.23	3	17.9
Φ (site) ρ (.)	84.1	1.17	0.22	3	18.0
Φ (group) ρ (.)	86.5	3.60	0.06	4	18.3
Φ (.) ρ (group)	86.9	4.03	0.05	4	18.7
Φ (.) ρ (site x group)	90.5	7.60	0.01	7	15.9
Φ (site x group) ρ (.)	90.6	7.73	0.01	7	16.0
Φ (site x group) ρ (site x group)	96.2	13.35	0.00	11	12.7
Φ (.) ρ (site x group x time)	110.3	27.45	0.00	19	7.6
Φ (site x group x time) ρ (.)	111.7	28.82	0.00	18	11.5
Φ (site x group x time) ρ (site x group x time)	118.9	35.98	0.00	23	5.8

Table 3 Estimates of survivorship (Φ) and capture probability (ρ) of *Chelodina longicollis* among groups (adult male, adult female, and juvenile) and between drainages (Inner North: low habitat connectivity; and West Belconnen: greater connectivity) in the Australian Capital Territory, Australia, 2020–2022

Site	Group	Φ (bi-annual)	Φ (annual)	ρ (bi-annual)
Inner North	Male	0.677 ± 0.288	0.459 ± 0.083	0.069 ± 0.052
	Female	0.673 ± 0.281	0.453 ± 0.079	0.070 ± 0.052
	Juvenile	0.688 ± 0.287	0.474 ± 0.082	0.070 ± 0.052
West Belconnen	Male	0.737 ± 0.317	0.543 ± 0.100	0.083 ± 0.064
	Female	0.742 ± 0.315	0.550 ± 0.099	0.086 ± 0.067
	Juvenile	0.757 ± 0.316	0.573 ± 0.100	0.085 ± 0.066

Discussion

Urbanization, road network and associated habitat fragmentation are among the greatest threats to wildlife inhabiting urban areas (Murray et al. 2019; Xu et al. 2019; Habrich et al. 2021). Even though some vertebrates do benefit from the increased food availability and habitat in urban and peri-urban areas (McKinney 2002; Bateman and Fleming 2012), few studies have directly demonstrated how lack of habitat connectivity in urban areas constrains survival and population parameters of freshwater turtles living in cities (Santoro et al. 2020; Auge et al. 2023). Our study helps to fill that gap

and shows that despite evidence of *C. longicollis* benefiting from urban waterways (Roe et al. 2011; Stokeld et al. 2014), we observed that population sizes do not increase steeply in larger urban ponds in areas with lower habitat connectivity (higher road network).

Our results showed that most of the parameters related to habitat and food requirements for *C. longicollis* were similar between the two distinctive drainages we studied. There was no significant difference in age and size of ponds between Inner North (low habitat connectivity) and West Belconnen (high habitat connectivity) drainages, and also no difference between phosphate concentration (one of the parameters for primary productivity) and prey biomass (secondary productivity). Only nitrate concentration differed in terms of productivity, and that is possibly attributed to the land use surrounding the ponds and the quality of urban runoff, as urban ponds tend to have higher concentration of nitrates compared to natural areas (Holzer 2014; Rooney et al. 2014). Despite this difference, the amount of turtle prey was not significantly different between drainages and food availability should not explain the differences in *C. longicollis* population parameters observed in the present study.

On the other hand, there were significant differences between the study areas in terms of how connected, or not, the stormwater pond systems were. Male, female and juvenile *C. longicollis* move on land, with an overland dispersal capacity of more than 8 km (Roe and Georges 2008; Kennett et al. 2009; Ferronato et al. 2014), and rainfall being one of the main triggers for dispersal and overland movements (Kennett et al. 2009), it is possible that habitat connectivity plays a major role in sustaining healthy turtle populations in urbanized landscapes. As the species regularly migrates between ponds, it is likely that habitat connectivity is an important factor in maintaining healthy turtle populations in urban areas. For example, the road network surrounding the ponds in the Inner north was twice as dense West Belconnen. Road mortalities are one of the main threats not only to *C. longicollis* (Ferronato et al. 2016; Santori et al. 2018), but for several species of freshwater turtles worldwide (Gibbs and Steen 2005; Langen et al. 2012). Additionally, the drain network within Inner North stormwater ponds (Fig. 2) is usually dry and only provides an opportunity for turtle movement through the drains during storms, when they are filled with stormwater. Alternatively, Ginninderra Creek in West Belconnen is unmodified and provides an avenue for turtle migrations during drier or wetter conditions. While the best supported model showed no difference in survivorship and capture probability between the two studied drainages, there was some support for competing models where Inner North turtles showed lower survival rates and capture probability. But we cannot discard that other factors might have also influenced the results observed, and future

investigation should focus on radio tracking and movement behaviour of *C. longicollis* (Ferronato et al. 2016) and nest predation rates.

The fact that proportionally turtle age structure was similar between Inner North and West Belconnen drainages and both drainages showing signs of turtle recruitment (Fig. 5), suggests that if turtles get to the stormwater ponds in either drainage, they will be able to establish and breed. However, once there is stimulus to migrate or nest (rainfall in Spring and Summer, Kennett et al. 2009; Ferronato et al. 2014; Santori et al. 2018), turtles in Inner North are likely to encounter more threats from roads and development, leading to mortality. It is possible that these combined factors might explain why turtle population sizes in the more connected drainage (West Belconnen) increased more steeply with increasing pond size than did population sizes in the less connected Inner North drainage. Larger ponds can provide more habitat, food and an increased carrying capacity, but these benefits could be counterbalanced by limits to dispersal and increased risk of mortality in low-connectivity habitats. By contrast, with higher connectivity the surrounding landscapes remains more permeable for animals dispersing on land and through natural channels, facilitating migration between and colonisation of ponds. A follow up study in these two distinct drainages might elucidate if survivorship of Inner North turtles does decline over the long term.

Highlighting the ability of *C. longicollis* to persist in connected urban landscapes was the recapture in the present study of a marked male individual, 14 years after and approximately 15 km downstream from its initial point of capture within the Ginninderra creek drainage (West Belconnen). In a previous investigation, another marked *C. longicollis* had been recaptured after eight years and approximately 6 km downstream in the Ginninderra creek drainage (Ferronato et al. 2017). The present finding expands the knowledge on *C. longicollis* survival and movement in an urbanized context. There is evidence of *C. longicollis* being recaptured after 22 years, 5.2 km overland from its initial point of capture, within a natural context in Booderee National Park (Roe et al. 2009), in addition to records of a juvenile *C. longicollis* recaptured after one and a half years, 10.6 km downstream between billabongs on the Latrobe River following a major flood, and a male *C. longicollis* recaptured after 6 years at Chalka Creek, 5.7 km downstream from its initial point of capture (Chessman 2018; Bruce Chessman *personal communication*), and another Australian turtle (*Emydura macquarii krefftii*) being recaptured 4 km downstream within the Burnett River (Hamann et al. 2008). In addition, recaptures of freshwater turtles elsewhere have shown different patterns, such as being recaptured over a much longer timespan, but within the same nature reserve (*Emydoidea blandingii* recaptured after 63 years; Nagle et al. 2017);

within a connected agricultural landscape (*Chrysemys picta* recaptured after up to four years and having dispersed up to 3.3 km; Bowne et al. 2006); and being recaptured much further away than our observation (> 50 km, *Graptemys geographica*) following a 10 year post-oil spill study on survival and homing within Kalamazoo River drainage in the USA (Otten et al. 2023).

A limitation of our study is that there were only four stormwater ponds available for turtle sampling within the lower sections of both drainages. Ideally, if available, more ponds could have been sampled to increase sample sizes and perhaps other drainages in the Canberra region representing low and high connectivity areas. Examples of studies on the impacts of urbanization on *C. longicollis* in greater Melbourne covered at least 55 ponds, although their focus was on wetland occupancy and a suite of site- and landscape-level metrics influencing it (Stokeld et al. 2014; Hamer et al. 2016). Despite our small sample size, the two distinct drainages (West Belconnen and Inner North) were ideal to study the effect of connectivity on turtles, as they showed many similarities in terms of pond area and food sources, but varied in habitat fragmentation and connectivity. Additionally, our connectivity metric (road network) is confounded with the urban to peri-urban gradient, so that while we are assuming that connectivity determined by the road network is the critical aspect of urbanization affecting turtle populations in this study, there could be additional factors that differ between the urban and peri-urban clusters that also contribute to the effects on turtles.

Our findings increase the knowledge of *C. longicollis* inhabiting urbanized landscapes and demonstrate that despite evidence of *C. longicollis* being resilient to urbanization (Roe et al. 2011; Stokeld et al. 2014; Ferronato et al. 2017), we showed that within a drainage with more habitat connectivity, population sizes increase more steeply with pond area, while that relationship is weaker in a less connected drainage, which may be related to their movement ability in the landscape. Although one of the main roles of stormwater ponds is to trap sediments and naturally filter stormwater (Ivanovsky et al. 2018), they do attract wildlife such as turtles, and biodiversity sensitive urban design might be considered during the planning and construction phase of this infrastructure (Garrard et al. 2018). Improving connectivity through approaches such as including buffer green spaces within urban pond surroundings (e.g. provide nesting habitat, Foley et al. 2012; Guzy et al. 2013) and maintaining natural channels and avoiding channelization of urban streams (Marsalek and Schreier 2009), or perhaps trying to retain water levels within stormwater drains, could help turtles to safely disperse and move through highly developed drainages and improve their persistence. Future monitoring in the West Belconnen and Inner North drainages can help

to elucidate if *C. longicollis* survival is affected over the long term, and how *C. longicollis* respond during droughts in less connected drainages, with potential higher risk of road mortality if animals are migrating in response to lower water levels in the ponds.

Acknowledgements We would like to thank all the volunteers involved in this citizen science project, who helped in the field work. We also would like to thank the Ginninderra Catchment Group and University of Canberra Institute for Applied Ecology for logistical support, and Bruce Chessman for providing references and sharing unpublished data, and the anonymous reviewers for their suggestions on the manuscript.

Author contributions Bruno de Oliveira Ferronato: Conceptualization, Methodology, Field Work, Data Analysis, Writing – Original Draft, Writing – Review and Editing, Funding Acquisition. Anke Maria Hoefler: Conceptualization, Methodology, Field Work, Writing – Original Draft, Writing – Review and Editing, Funding Acquisition. Isobel Booksmythe: Conceptualization, Methodology, Data Analysis, Writing – Original Draft, Writing – Review and Editing. Rod Ubrihien: Conceptualization, Methodology, Data Analysis, Writing – Original Draft, Writing – Review and Editing. Arthur Georges: Conceptualization, Methodology, Writing – Original Draft, Writing – Review and Editing.

Funding Funding for this project was provided by the Communities Environment Program (CEP 80155, 80156), ACT Environmental Grants (ENV202200022) and the Conservation Research branch of the Office of Nature Conservation (ACT Government).

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval This project was conducted with approvals and permits from the ACT Licensing and Compliance (LT202011) and University of Canberra Animal Ethics Committee (n.3379).

Informed consent Not applicable.

Competing interests The authors declare no competing interests.

References

- Auge AC, Blouin-Demers G, Hasler CT, Murray DL (2023) Demographic evidence that development is not compatible with sustainability in semi-urban freshwater turtles. *Anim Conserv*. <https://doi.org/10.1111/acv.12903>
- Australian Bureau of Meteorology (2023) Climate Data online. <http://www.bom.gov.au/act/?ref=hdr>. Accessed 24 June 2023
- Bárcenas-García A, Michalski F, Morgan WH, Smith RK, Sutherland WJ, Gibbs JP, Norris D (2022) Impacts of dams on freshwater turtles: a global review to identify conservation solutions. *Trop Conserv Sci* 15:19400829221103709
- Bateman PW, Fleming PA (2012) Big city life: carnivores in urban environments. *J Zool* 287:1–23
- Birnie-Gauvin K, Nielsen J, Frandsen SB, Olsen HM, Aarestrup K (2020) Catchment-scale effects of river fragmentation: a case study on restoring connectivity. *J Environ Manage* 264:110408
- Bowne DR, Bowers MA, Hines JE (2006) Connectivity in an agricultural landscape as reflected by interpond movements of a freshwater turtle. *Conserv Biol* 20:780–791
- Braaker S, Moretti M, Boesch R, Ghazoul J, Obrist MK, Bontadina F (2014) Assessing habitat connectivity for ground-dwelling animals in an urban environment. *Ecol Appl* 24:1583–1595
- Brodie JF, Paxton M, Nagulendran K, Balamurugan G, Clements GR, Reynolds G, Jain A, Hon J (2016) Connecting science, policy, and implementation for landscape-scale habitat connectivity. *Conserv Biol* 30:950–961
- Bureau of Meteorology (2022) Special Climate Statement 75 – Australia’s wettest November on record. <http://www.bom.gov.au/cli-mate/current/statements/scs75.pdf>. Accessed 24 June 2023
- Burgin S, Ryan M (2008) Comparison of sympatric freshwater turtle populations from an urbanized Sydney catchment. *Aquat Conserv* 18:1277–1284
- Burnham KP, Anderson DR (1998) Model selection and inference: a practical information-theoretic approach. Springer, New York
- Chessman BC (1984a) Evaporative water loss from three south-eastern Australian species of water turtle. *Aust J Zool* 32:649–655
- Chessman BC (1984b) Food of the snake-necked turtle, *Chelodina longicollis* (Shaw) (Testudines: Chelidae) in the Murray Valley, Victoria and New South Wales. *Aust Wildl Res* 11:573–578
- Chessman BC (2018) Slow and unsteady: growth of the Australian eastern long-necked turtle near the southern end of its natural range. *Aust J Zool* 66:77–83
- Cooch E, White G (2014) Using MARK – a Gentle Introduction, 13th edn. <http://www.phidot.org/software/mark/docs/book/>. Accessed 15 May 2023
- Cushman SA (2006) Effects of habitat loss and fragmentation on amphibians: a review and prospectus. *Biol Conserv* 128:231–240
- Delaney KS, Busteed G, Fisher RN, Riley SP (2021) Reptile and amphibian diversity and abundance in an urban landscape: impacts of fragmentation and the conservation value of small patches. *Ichthyol Herpetol* 109:424–435
- Eskew EA, Price SJ, Dorcas ME (2010) Survival and recruitment of semi-aquatic turtles in an urbanized region. *Urban Ecosyst* 13:365–374
- Ferronato BO, Merchant ME, Marques TS, Verdade LM (2009) Characterization of innate immune activity in *Phrynops geoffroanus* (Testudines: Chelidae). *Zoologia* 26:747–752
- Ferronato BO, Roe JH, Georges A (2014) Reptile bycatch in a pest-exclusion fence established for wildlife reintroductions. *J Nat Conserv* 22:577–585
- Ferronato BO, Roe JH, Georges A (2016) Urban hazards: spatial ecology and survivorship of a turtle in an expanding suburban environment. *Urban Ecosyst* 19:415–428
- Ferronato BO, Roe JH, Georges A (2017) Responses of an Australian freshwater turtle to drought-flood cycles along a natural to urban gradient. *Austral Ecol* 42:442–455
- FitzGibbon SI, Putland DA, Goldizen AW (2007) The importance of functional connectivity in the conservation of a ground-dwelling mammal in an urban Australian landscape. *Landsc Ecol* 22:1513–1525
- Foley SM, Price SJ, Dorcas ME (2012) Nest-site selection and nest depredation of semi-aquatic turtles on golf courses. *Urban Ecosyst* 15:489–497
- Fuller MR, Doyle MW, Strayer DL (2015) Causes and consequences of habitat fragmentation in river networks. *Ann N Y Acad Sci* 1355:31–51
- Galster JC, Pazzaglia FJ, Germanoski D (2008) Measuring the impact of urbanization on channel widths using historic aerial

- photographs and modern surveys. *J Am Water Resour Assoc* 44:948–960
- Garrard GE, Williams NS, Mata L, Thomas J, Bekessy SA (2018) Biodiversity sensitive urban design. *Conserv Lett* 11:e12411
- Georges A, Norris RH, Wensing L (1986) Diet of the freshwater turtle *Chelodina longicollis* (Testudines: Chelidae) from the coastal dune lakes of the Jervis Bay Territory. *Aust Wildl Res* 13:301–308
- Gibbs JP, Steen DA (2005) Trends in sex ratios of turtles in the United States: implications of road mortality. *Conserv Biol* 19:552–556
- Gido KB, Whitney JE, Perkin JS, Turner TF (2015) Fragmentation, connectivity and fish species persistence in freshwater ecosystems. In: Closs G, Krkosek M, Olden J (eds) *Conservation of Freshwater fishes*. Cambridge University Press, Cambridge, pp 292–323. <https://doi.org/10.1017/CBO9781139627085>.
- Graham T, Georges A, McElhinney N (1996) Terrestrial orientation by the eastern long-necked turtle, *Chelodina longicollis*, from Australia. *J Herpetol* 30:467–477
- Guzy JC, Price SJ, Dorcas ME (2013) The spatial configuration of greenspace affects semi-aquatic turtle occupancy and species richness in a suburban landscape. *Landscape Urban Plan* 117:46–56
- Habrich AK, Lawrence ER, Fraser DJ (2021) Varying genetic imprints of road networks and human density in north American mammal populations. *Evol Appl* 14:1659–1672. <https://doi.org/10.1111/evo.13232>
- Hamann M, Schauble CS, Emerick SP, Limpus DJ, Limpus CJ (2008) Freshwater turtle populations in the Burnett River. *Mem Queensl Mus* 52:221–232
- Hamer AJ, Harrison LJ, Stokeld D (2016) Road density and wetland context alter population structure of a freshwater turtle. *Austral Ecol* 41:53–64
- Hassani MSE, Slimani T, Bonnet X (2019) Morphological and physiological assessments reveal that freshwater turtle (*Mauremys leprosa*) can flourish under extremely degraded-polluted conditions. *Chemosphere* 220:432–441
- Holzer KA (2014) Amphibian use of constructed and remnant wetlands in an urban landscape. *Urban Ecosyst* 17:955–968
- Isdell RE, Chambers RM, Bilkovic DM, Leu M (2015) Effects of terrestrial-aquatic connectivity on an estuarine turtle. *Divers Distrib* 21:643–653
- Ivanovsky A, Belles A, Criquet J, Dumoulin D, Noble P, Alary C, Billon G (2018) Assessment of the treatment efficiency of an urban stormwater pond and its impact on the natural downstream watercourse. *J Environ Manage* 226:120–130
- Johnson AM, Karels TJ (2016) Partitioning the effects of habitat fragmentation on rodent species richness in an urban landscape. *Urban Ecosyst* 19:547–560
- Kang W, Minor ES, Park CR, Lee D (2015) Effects of habitat structure, human disturbance, and habitat connectivity on urban forest bird communities. *Urban Ecosyst* 18:857–870
- Kennett RM, Georges A (1990) Habitat utilization and its relation to growth and reproduction of the eastern long-necked turtle, *Chelodina longicollis* (Testudinata: Chelidae), from Australia. *Herpetologica* 46:22–33
- Kennett R, Roe J, Hodges K, Georges A (2009) *Chelodina longicollis* (Shaw 1784)- eastern long-necked turtle, common long-necked turtle, common snake-necked turtle. *Chelon Res Monogr* 5:0311–0318
- Kuchling G (2000) Conservation strategies for remnant turtle populations: the Western Australian swamp turtle *Pseudemys umbrina* recovery programme. *Zugleich Kataloge Des OÖ Landesmuseums Neue Folge* 149:179–188
- Langen TA, Gunson KE, Scheiner CA, Boulter JT (2012) Road mortality in freshwater turtles: identifying causes of spatial patterns to optimize road planning and mitigation. *Biodivers Conserv* 21:3017–3034
- Lebreton JD, Burnham KP, Colbert J, Anderson DR (1992) Modelling survival and testing biological hypotheses using marked animals: a unified approach with case studies. *Ecol Monogr* 62:67–118
- Li G, Fang C, Li Y, Wang Z, Sun S, He S, Qi W, Bao C, Ma H, Fan Y, Feng Y (2022) Global impacts of future urban expansion on terrestrial vertebrate diversity. *Nat Commun* 13:1628
- Liu Z, He C, Wu J (2016) The relationship between habitat loss and fragmentation during urbanization: an empirical evaluation from 16 world cities. *PLoS ONE* 11:e0154613
- Luiselli L, Diagne T, McGovern P (2021) Prioritizing the next decade of freshwater turtle and tortoise conservation in West Africa. *J Nat Conserv* 60:125977
- Ma J, Li J, Wu W, Liu J (2023) Global forest fragmentation change from 2000 to 2020. *Nat Commun* 14:3752
- Marsalek J, Schreier H (2009) Innovation in stormwater management in Canada: the way forward. *Water Qual Res J* 44:v–x
- McKinney ML (2002) Urbanization, biodiversity and conservation. *Bioscience* 52:883–890
- Moll RJ, Cepek JD, Lorch PD, Dennis PM, Tans E, Robison T, Millspaugh JJ, Montgomery RA (2019) What does urbanization actually mean? A framework for urban metrics in wildlife research. *J Appl Ecol* 56:1289–1300
- Murray MH, Sanchez CA, Becker DJ, Byers KA, Worsley-Tonks KEL, Craft ME (2019) City sicker? A meta-analysis of wildlife health and urbanization. *Front Ecol Environ* 17:575–583
- Nagle RD, Kinney OM, Gibbons JW, Congdon JD (2017) A simple and reliable system for marking hard-shelled turtles: the North American Code. *Herpetol Rev* 48:327–330
- Nguyen H, Wheeler MC, Hendon H, Lim EP, Otkin JA (2021) The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. *Weather Clim Extrem* 32:100321
- Otten JG, Williams L, Refsnider JM (2023) Assessing translocation success and long-distance homing in riverine turtles 10 years after a freshwater oil spill. *Conserv Sci Pract* 5:e12922
- Rees M, Roe JH, Georges A (2009) Life in the suburbs: behavior and survival of a freshwater turtle in response to drought and urbanization. *Biol Conserv* 142:3172–3181
- Riley SP, Sauvajot RM, Fuller TK, York EC, Kamradt DA, Bromley C, Wayne RK (2003) Effects of urbanization and habitat fragmentation on bobcats and coyotes in southern California. *Conserv Biol* 17:566–576
- Rizkalla CE, Swihart RK (2006) Community structure and differential responses of aquatic turtles to agriculturally induced habitat fragmentation. *Landscape Ecol* 21:1361–1375
- Roe JH, Georges A (2007) Heterogeneous wetland complexes, buffer zones, and travel corridors: landscape management for freshwater reptiles. *Biol Conserv* 135:67–76
- Roe JH, Georges A (2008) Terrestrial activity, movements and spatial ecology of an Australian freshwater turtle, *Chelodina longicollis*, in a temporally dynamic wetland system. *Austral Ecol* 33:1045–1056
- Roe JH, Brinton AC, Georges A (2009) Temporal and spatial variation in landscape connectivity for a freshwater turtle in a temporally dynamic wetland system. *Ecol Appl* 19:1288–1299
- Roe JH, Rees M, Georges A (2011) Suburbs: dangers or drought refugia for freshwater turtle populations? *J Wildl Manage* 75:1544–1552
- Rooney RC, Foote L, Krogman N, Pattison JK, Wilson MJ, Bayley SE (2015) Replacing natural wetlands with stormwater management facilities: Biophysical and perceived social values. *Water Res* 73:17–28
- Santo-Silva EE, Almeida WR, Tabarelli, Peres CA (2016) Habitat fragmentation and the future structure of tree assemblages in a fragmented Atlantic forest landscape. *Plant Ecol* 217:1129–1140
- Santori C, Spencer RJ, Van Dyke JU, Thompson MB (2018) Road mortality of the eastern long-necked turtle (*Chelodina longicollis*)

- along the Murray River, Australia: an assessment using citizen science. *Aust J Zool* 66:41–49. <https://doi.org/10.1071/ZO17065>
- Santoro A, Chambers JM, Robson BJ, Beatty SJ (2020) Land use surrounding wetlands influences urban populations of a freshwater turtle. *Aquat Conserv* 30:1050–1060
- Seber GAF (1982) The estimation of animal abundance and related parameters, 2nd edn. Griffin, London
- Serrano F, Pita R, Mota-Ferreira M, Beja P, Segurado P (2020) Landscape connectivity affects individual survival in unstable patch networks: the case of a freshwater turtle inhabiting temporary ponds. *Freshw Biol* 65:540–551
- Simkin RD, Seto KC, McDonald RI, Jetz W (2022) Biodiversity impacts and conservation implications of urban land expansion projected to 2050. *Proc Natl Acad Sci* 119:e2117297119
- Souza FL, Abe AS (2000) Feeding ecology, density and biomass of the freshwater turtle, *Phrynops geoffroanus*, inhabiting a polluted urban river in south-eastern Brazil. *J Zool* 252:437–446
- Stokeld D, Hamer AJ, van der Ree R, Pettigrove V, Gillespie G (2014) Factors influencing occurrence of a freshwater turtle in an urban landscape: a resilient species? *Wildl Res* 41:163–171
- van Dijk AIJM, Beck HE, Crosbie RS, de Jeu RAM, Liu YY, Podger GM et al (2013) The Millennium Drought in Southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resour Res* 49:1040–1057. <https://doi.org/10.1002/wrcr.20123>
- Watson DM, Doerr VA, Banks SC, Driscoll DA, van der Ree R, Doerr ED, Sunnucks P (2017) Monitoring ecological consequences of efforts to restore landscape-scale connectivity. *Biol Conserv* 206:201–209
- Xu X, Xie Y, Qi K, Luo Z, Wang X (2018) Detecting the response of bird communities and biodiversity to habitat loss and fragmentation due to urbanization. *Sci Total Environ* 624:1561–1576

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.