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Road mortality of the eastern long-necked turtle (*Chelodina longicollis*) along the Murray River, Australia: an assessment using citizen science

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Abstract. Turtles face a variety of threats (e.g. habitat destruction, introduced predators) that are pushing many species towards extinction. Vehicle collisions are one of the main causes of mortality of adult freshwater turtles. To conceptualise the level of threat that roads pose to Australians turtles, we analysed data gathered through the citizen science project TurtleSAT along the Murray River. We recorded 124 occurrences of turtle road mortality, which included all three local species (*Chelodina expansa*, *Chelodina longicollis*, and *Emydura macquarii*). *Chelodina longicollis* was the most commonly reported species killed on roads. We found that rain and time of year affect the likelihood of *C. longicollis* being killed on roads: increased turtle mortality is associated with rain events and is highest during the month of November, which coincides with their nesting season. *Chelodina longicollis* was most likely to be killed on the Hume Highway and roads around major urban centres; therefore, we recommend that governing bodies focus management practices and increase awareness at these locations. The degree of road mortality that we detected in this study requires mitigation, as it may contribute to the decline of *C. longicollis* along the Murray River.

Additional keywords: conservation, freshwater turtles, MaxEnt, road ecology, roadkill, TurtleSAT, wildlife management.

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Introduction

As the human population and urban development have expanded, road networks have become one of the most prominent terrestrial habitat modifications (Forman and Alexander 1998; Trombulak and Frissell 2000). Roads negatively affect wildlife in many ways, including decreasing habitat quality, genetically isolating populations, and directly killing individuals (Aresco 2005*a*; Lee *et al*. 2010; van der Ree *et al*. 2015). For instance, across five states within the United States vehicle collisions caused the deaths of 140 000 animals, including amphibians, reptiles, mammals and birds in only one month (Havlick 2004). Thus, population dynamics of many species are likely affected by roads (Trombulak and Frissell 2000; Steen and Gibbs 2004; Steen *et al*. 2006). Road impacts can be especially significant for aquatic animals that can also travel overland, such as freshwater turtles (Hamer *et al*. 2016). Many freshwater turtles cross land to find suitable nesting grounds, to escape drying water bodies, or to disperse to new wetlands for foraging and reproduction (Steen *et al*. 2006; Roe and Georges 2008). Due to increased road density and traffic volume, road mortality has become an issue for freshwater turtles globally. This problem is particularly critical for turtles due to their life histories: they are long-lived animals with few predators once they reach adulthood, and are characterised by delayed sexual maturity and low recruitment (Beaudry *et al*. 2008). Therefore, their populations are not able to recover quickly from mortality of even a small number of reproductive individuals (Congdon *et al*. 1993, 1994; Spencer *et al*. 2017).

Overland movements of turtles can be affected by weather and time of year, factors that in turn can influence the likelihood of road mortality. For example, many freshwater turtles are killed during their breeding seasons, as they move on land to find nesting grounds (Haxton 2000; Crump *et al*. 2016). Furthermore, road characteristics can influence the likelihood of turtle road mortality, with major highways or roads with high traffic volumes causing the highest rates of mortality (Haxton 2000).

Finally, as landscape characteristics such as interwetland distance and wetland configuration can influence space use by turtles (Roe and Georges 2008), the geographical features of certain locations may enhance the likelihood of turtle road mortality due to more frequent local movements.

Australia is the 11th most turtle diverse country on Earth, with 31 native turtle species (25 of which live in fresh water: Wilson and Swan 2010; Mittermeier *et al*. 2015). Along the Murray River, the largest Australian river catchment, freshwater turtles have declined significantly (Chessman 2011). Three species of turtles inhabit the Murray River: the broad-shelled turtle (*Chelodina expansa*), the eastern long-necked turtle (*Chelodina longicollis*), and the Murray River short-necked turtle (*Emydura macquarii*; Thompson 1983; Spencer and Thompson 2005). In some areas along the Murray River, more than 85% of turtle eggs are depredated by introduced European foxes (*Vulpes vulpes*; Thompson 1983; Spencer 2002), and adult turtles face several threats, which include road mortality (Spencer *et al*. 2017). In particular, a 91% decline in *C. longicollis* numbers has been detected in the mid-Murray River over the last 40 years (Chessman 2011). However, despite road mortality being recognised as a threat to these turtles (Spencer *et al*. 2017), to date there has been no specific assessment of this issue. As the Murray River is more than 2000 km long, an assessment of road mortality within its catchment would require the collection of large amounts of data covering a wide geographic area, which so far has been a limiting factor. Citizen science involves the wider public in research projects (Silvertown 2009; Hacklay 2013), and is an excellent way of collecting substantial datasets over large geographic areas (Dickinson *et al*. 2010; Paul *et al*. 2014). Citizen scientists have recently been involved in many wildlife road mortality projects globally, which demonstrate the value of this branch of science for conservation (Paul *et al*. 2014; Vercayie and Herremans 2015; Shilling and Waetjen 2015; Dwyer *et al*. 2016; Heigl *et al*. 2016, 2017).

With this descriptive study, we aimed to explain patterns in turtle road mortality along the Murray River. Here, we used data collected by citizen scientists through an online app (i.e. TurtleSAT), to identify (1) which species are killed most often on roads, and whether adult females are killed most often, possibly due to nesting behaviour. We expected *C. longicollis* to be the most affected by road mortality, as this is the species that travels on land the most (Burgin and Renshaw 2008). Focussing on *C. longicollis*, we then tested (2) the relationships between this species' road mortality, weather, and time of year. We anticipated more *C. longicollis* to die on roads during their nesting season, and following rain events due to increased overland movements (Kennett and Georges 1990). Finally, we assessed (3) which landscape and climatic characteristics are associated with the distribution of *C. longicollis* road mortality in this region. This information is fundamental to determine the level of threat posed by roads to turtles along the Murray River. In addition, our study provides information critical to understanding the driving forces behind the declines of freshwater turtles in Australia, so that conservation action and management strategies for freshwater turtles can be developed.

Materials and methods

The citizen science project TurtleSAT (http://www.turtlesat.org.au) was used to collect data on road mortality along the Murray River Catchment in south-eastern Australia. TurtleSAT was launched in May 2014; however, some backdated sightings were uploaded by users, and we used all records available by April 2017. We identified all observations within our study area (Fig. S1, Supplementary Material) that were classified by citizen scientists as 'road kill' from the TurtleSAT database, as well as unclassified observations accompanied by a photograph of a road-killed turtle, using ArcGIS 10.3.1 (ESRI 2015). If two observations were made by the same user and were uploaded at least one week apart or at least 1 km apart, we assumed they were of different turtles. One record of road-killed *C. expansa* was removed as a double count. Then, as a general description of the TurtleSAT road-kill dataset, we collated the information about species, age class, sex, and when each observation was uploaded.

We conducted all our subsequent statistical analyses using observations of *C. longicollis* only. All tests were computed using R Software (R Core Team 2017) unless specified otherwise. First, we collected data on daily maximum temperature (°C), total daily rainfall (mm) and total daily solar exposure (MJ m^{-2}) from the closest weather station to each *C. longicollis* road-kill observation, prioritising stations with quality-controlled data (Bureau of Meteorology 2018). We chose the highest value between the day of each observation and the day before, to account for weather conditions of the 24 h before the mortality being observed, since the specific timing of mortality is unknown. The same procedure was used to collect identical data for a random day in which a dead *C. longicollis* was not observed. We selected the random days between the date of the first and last road-killed turtle recorded in the study area, excluding the winter months of turtle inactivity (June, July and August). The weather variables did not correlate with one another (Pearson's Correlations were all <0.7), so we used all of them as independent variables. We tested both the influence of month and weather on the probability of road mortality in *C. longicollis* by computing logistic regressions using PROC GLIMMIX (SAS Institute Inc. 2016).

To assess the influence of weather on the likelihood of a *C. longicollis* being hit on the road according to its individual characteristics, we ran two separate ANOVAs to identify differences in temperature, rainfall and solar exposure between sexes and age groups, and any interaction between these traits. For each of the ANOVAs, we adjusted our α with a Bonferroni correction ($\alpha = 0.025$), to account for the effects of multiple comparisons on our Type I error. As the weather data were not normally distributed, we computed the ANOVAs with log-transformed data. To account for deviations from normality, we also ran a Kruskal–Wallis test on ranked weather data. The results were not distinguishable, so we reported the results of the ANOVAs with the log-transformed weather data.

Finally, we modelled the distribution of *C. longicollis* road mortalities to investigate the geographic drivers of road mortality, using (1) road size, (2) climate, (3) distance to water, (4) spatial density of water bodies, (5) distance to forest and (6) distance to urban areas as environmental predictors (Supplementary Material). Since our dataset comprised presence-only data, we used MaxEnt 3.4.0 to build our spatial models (Phillips *et al*. 2006; Elith *et al*. 2006). MaxEnt is considered a robust modelling tool that can handle small sample sizes (Wisz *et al*. 2008). We interpreted the MaxEnt logistic output as the probability of occurrence of *C. longicollis* road-kill (Elith *et al*. 2011).

Ten observations of dead *C. longicollis* were reported as more than 500 m away from any road, possibly due to phone GPS malfunctioning, so we removed these and used 81 observations for our model. We used the default settings of MaxENT, apart from changing the number of random test points to 25% (Young *et al*. 2011; Brown *et al*. 2014), the maximum iterations to 5000 (Young *et al*. 2011; Wu and Murphy 2015), and not removing duplicate observations. We replicated each model 15 times (Young *et al*. 2011) and averaged the results of their logistic outputs.

As TurtleSAT does not have a strict survey protocol, spatial bias could limit the realism of our analysis (Phillips *et al*. 2009; Geldmann *et al*. 2016). To correct for possible bias, we ran and compared four different MaxEnt models (Supplementary Material), consisting of a non-corrected model, two models for which we added a bias file ('background model' and 'density model'), and a thinned-data model ('thinned model'). The four models were evaluated using their area under the curve (AUC), AICc values (Zeng *et al*. 2016), and Schoener's D statistic for niche overlap (Warren *et al*. 2008; Supplementary Material). Finally, we also compared the ranks of permutation importance and percentage contribution of each environmental variable between models (Supplementary Material). We used the '10 percentile training presence logistic threshold' as a threshold to classify a location as 'likely' or 'unlikely' to cause turtle road-kill (Kramer-Schadt *et al*. 2013).

Results

Between 1 January 2006 and 29 April 2017, 1349 turtles were reported by TurtleSAT users within the Murray River Catchment (Fig. S1, Supplementary Material), 32% of which were dead ($n = 427$). The cause of death was not stated in 46% of the cases. The most commonly reported cause of mortality was roads (29% of deaths, $n = 124$), followed by predation by foxes (10% of deaths; Fig. S2, Supplementary Material). Most of the turtles found dead on roads were *C. longicollis* ($n = 91$), followed by *C. expansa* ($n = 17$) and then by *E. macquarii* ($n = 4$), with $n = 12$ turtles not identified to species level (Fig. S3, Supplementary Material).

Age group was not classified for 43.5% of road-killed turtles, but, of the age-classified turtles, 93% were adults (Table 1). In addition, 76% of all turtles ($n = 94$) were not classified as 'adult male', 'adult female' or 'juvenile'. Of the adult turtles for which sex was determined ($n = 25$), $n = 18$ were 'adult females' (Table 1). *Chelodina expansa* was killed only in autumn, *E. macquarii* was killed in autumn and spring, whereas *C. longicollis* was killed on roads year-round (Fig. 1).

There were significant month and rainfall effects on the likelihood of road mortality in *C. longicollis* (Table 2; Table S1, Supplementary Material). Significantly more *C. longicollis* deaths occurred during the month of November than in any other month. Likewise, mortality increased with increasing rainfall. We subsequently tested whether the interaction between month and rainfall was significant to determine whether high mortality during November was driven by higher rainfall. This interaction was not significant ($F_{8,157} = 1.20$, $P = 0.302$). Thus, high rainfall drives higher mortality regardless of month, but mortality is still highest during November. An ANOVA found that rainfall differs significantly across months ($F_{8,177} = 5.30$, $P < 0.001$) and Tukey tests revealed it is significantly higher in November than in January, October, December, and September ($P \leq 0.05$). Thus, high rainfall might partially drive high mortality rates in November. Juvenile *C. longicollis* died during or after days with significantly greater solar exposure compared with adults (Tables S2 and S3, Supplementary Material). There was no other significant difference in the effect of weather on the likelihood of road mortality in *C. longicollis* among identified age groups or sexes (Tables S4–S7, Supplementary Material).

Roads were the main reported cause of death for *C. longicollis* (Fig. S4, Supplementary Material), and most *C. longicollis* were reported dead along dual carriageways (i.e. divided highway; Fig. S5, Supplementary Material). All spatial models for *C. longicollis* had AUC values >0.9. The model corrected with a Gaussian density of observations as bias layer had the lowest AICc score (Table 3). All Schoener's D values were $\geq$0.70, which indicates that all the models had a high degree of similarity and overlap (Table S8, Supplementary Material), and the effect sizes of each variable did not significantly differ among them (Fig. 2; Table S9, Supplementary Material). The likelihood of road mortality in *C. longicollis* was highest along the M31 (Hume Highway), and on roads close to cities such as Canberra, Albury, Shepparton and Adelaide (Fig. 3).

Discussion

We analysed the data collected through the citizen science project TurtleSAT along the Murray River to assess the demography of turtle mortality, if weather and season influence

Table 1. Count of road-killed turtles by sex and age

	Age			Sex			
	Adult	Juvenile	Unknown	Female	Male	Juvenile	Unknown
C. expansa	10	0	7	8	1	0	8
C. longicollis	46	5	40	8	6	5	72
E. macquarii	2	0	2	2	0	0	2
Unknown	7	0	5	0	0	0	12
Total	65	5	54	18	7	5	94

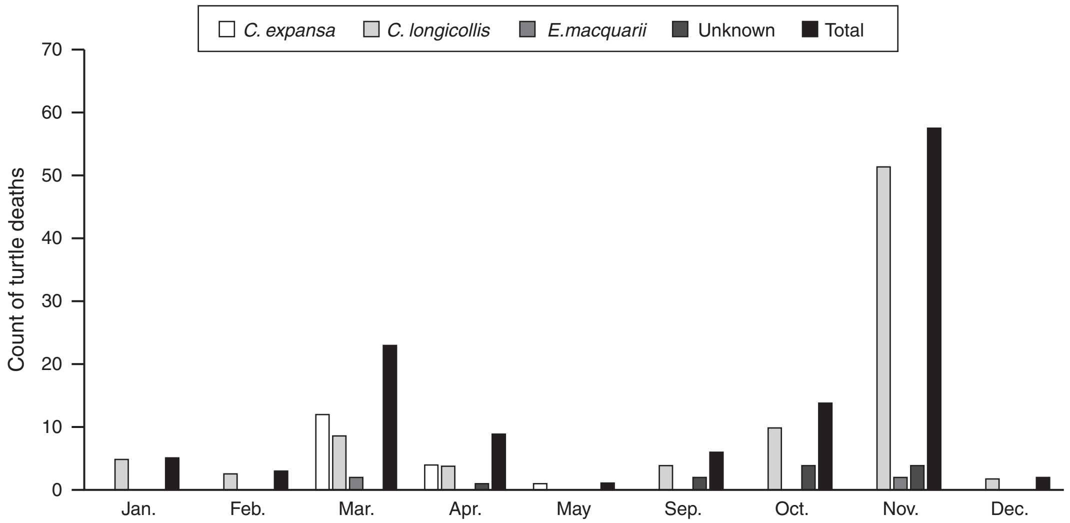

Fig. 1. Turtle mortality on roads along the Murray River in each month of the study. Most turtles were killed in March, October and November. This graph excludes three sightings reported during the winter months (two *C. longicollis* in July and one unidentified individual in August).

Table 2. Statistical results of SAS logistic regression testing the effects of month and weather on the probability of road mortality in *C. longicollis*

	d.f.	Model error (d.f.)	*F*	*P*
Month	8	165	3.18	0.002
Rainfall	1	165	11.69	<0.001
Temperature	1	165	1.98	0.161
Solar exposure	1	165	2.09	0.150

Table 3. Average AICc and AUC values for the 15 repeats of the five models for *C. longicollis*

AICc was calculated with raw outputs, AUC with logistic outputs. Numbers in parentheses are standard deviations

Model	AICc	AUC_{train}	AUC_{test}	AUC_{diff}
No corrections	1288.55 (37.00)	0.97 (0.004)	0.95 (0.02)	0.02
Thinned	1297.44 (392.51)	0.95 (0.007)	0.90 (0.03)	0.05
Density	1280.57 (24.25)	0.96 (0.003)	0.95 (0.01)	0.01
Background	1386.88 (72.61)	0.97 (0.005)	0.93 (0.02)	0.04

this mortality, and finally to investigate where turtles are hit the most. We were able to identify the turtle species most affected by this threat, as well as detect relationships between seasonality, weather and road type with road mortality. Our results highlight the usefulness of citizen science, and inform both spatial ecology and management practices that are urgently needed for turtle conservation.

As expected, *C. longicollis* was the species most frequently found killed on roads in our study area. Notably, *C. longicollis* has declined the most in the mid-Murray River (Chessman 2011). *Chelodina longicollis* travels on land extensively and can remain away from water for several months (Roe 2007; Roe and Georges 2008), unlike *E. macquarii* and *C. expansa.* *Chelodina longicollis* is an ephemeral wetland specialist that moves overland to exploit the high productivity of newly flooded water bodies (Kennett and Georges 1990). Our result is therefore intuitive based on this behaviour, as well as their more widespread geographic range; *C. longicollis* is often found in small water bodies such as farm dams away from the Murray River, unlike the other two species, which are tied to the river and nearby wetlands (Chessman 1988).

More adult turtles were found dead than juveniles of *C. longicollis* and the two other turtle species, although age-class was not reported for many carcasses. Population models based on Australian freshwater turtles suggest that for each 1% increase in adult mortality per year, the population extinction risk increases by ~40% (Spencer *et al*. 2017). Therefore, this is a conservation issue that requires urgent management. Turtles are long-lived organisms with delayed sexual maturity, and adult survival is critical for maintaining populations (Brooks *et al*. 1991). As mortality of adult turtles increases, populations decrease in size (Spencer *et al*. 2017), and these declines may be exacerbated by nest predation by foxes (Thompson 1983). However, it is important to acknowledge that dead adults may be more visible than juveniles to the citizens who participated in TurtleSAT, so an element of bias cannot be excluded.

Among the individuals that were sexed we observed a small female bias, but most dead turtles were not sexed (e.g. 79% of *C. longicollis*). This may be because *C. longicollis* is difficult to sex (Thompson 1983). Thus, a more precise investigation is needed to determine sex-specific road mortality risk. Road mortality of *C. longicollis* in periurban Sydney was not sex-related (Ryan 2014), and there was no difference in the proportion of female *C. longicollis* between sites of high and low road density throughout greater Melbourne (Hamer *et al*. 2016). However, female biases in road-killed turtles occur elsewhere in the world. In North America, female turtles of various species suffer higher rates of road mortality than males (Aresco 2005*a*; Steen *et al*. 2006). Female biases in road

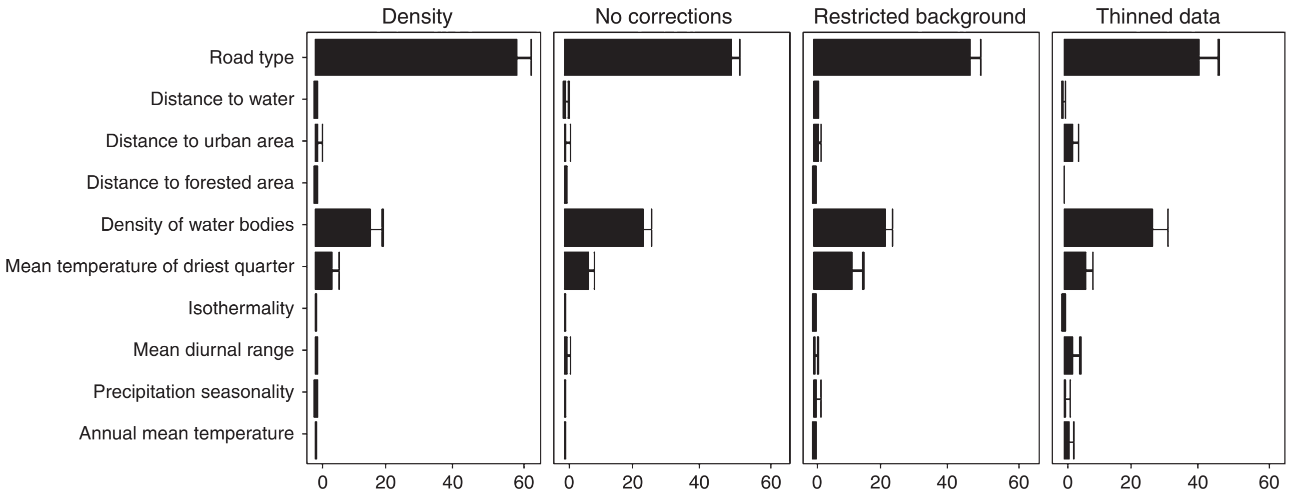

Fig. 2. Percentage of contribution to the model (*x*-axis) of each variable (*y*-axis) did not differ significantly between models for *C. longicollis*. Road type is the variable that contributed the most to the probability distribution of road mortality along the Murray River, regardless of the type of model.

mortality likely occur because female turtles move overland to nest. High female mortality may result in male-biased sex ratios, which could lead to reduced recruitment (Aresco 2005*a*). If turtle populations lose their reproductive capacity due to high female-biased mortality, they may eventually become locally extinct (Aresco 2005*a*). Due to their longevity, a skew in the sex ratio of a turtle population may not be apparent without close study, making a population seem healthy only because of the presence of adult males (Gooley 2010). Since our results suggest that there could be a female bias in turtle road mortality near the Murray River, conservation measures should consider the seasonality of road mortality due to nesting, and its long-term consequences, as a precaution before further investigation.

Most turtle road mortality along the Murray River coincided with the three local species' nesting periods (Fig. 1), which occur from October to December for *C. longicollis* and *E. macquarii*, and during March and April for *C. expansa* (Goode and Russell 1968; Thompson 1983). It is important to remember that citizen-collected data do not follow a rigorous and randomised schedule, so the observed seasonality could also reflect an increase in citizen scientists' use of TurtleSAT during spring and summer, especially around these nesting periods. Nevertheless, *C. longicollis* were found dead on roads year-round (Fig. 1), which may be explained by the vagrant nature of this species. In particular, the likelihood of road mortality in *C. longicollis* was significantly higher in the month of November, their peak nesting period, and during or after rain events. The overland movements of *C. longicollis* usually coincide with rainfall (Kennett *et al*. 2009). The observed relationship between road mortality and weather suggests that spring rain events may act as a cue for *C. longicollis* to emerge from aestivation and move to newly formed swamps, or as a nesting cue (Goode and Russell 1968; Kennett and Georges 1990), and this in turn may affect the likelihood of crossing roads and being hit. Indeed, November showed a peak of rainfall compared with most of the other months, and therefore it is possible that the rainfall effect may have been intensified by the coincidence with the nesting season, or vice versa. An experimental approach would be valuable to discriminate the possibly synergistic effects of rainfall and time of year.

Chelodina expansa and *E. macquarii* also nest predominantly after rain events (Goode and Russell 1968; Booth 2010; Chessman 2011), so the likelihood of road mortality of all three species may be increased by rainfall, but more data are needed to support this conclusion. Additionally, rain may make it harder for drivers to see turtles on the road. Finally, juvenile *C. longicollis* were killed during or after significantly sunnier days compared with adults. This difference could be due to juveniles requiring brighter light to move effectively on land, and/or responding to different cues to emerge from a wetland.

Our MaxEnt spatial model highlighted the major influences that road size, spatial density of water bodies, and temperature have on the likelihood of road mortality in *C. longicollis* (Fig. 2). All other variables contributed little to the models. Roads with higher vehicle speed and traffic volume tend to cause greater wildlife mortality (Trombulak and Frissell 2000; Joyce and Mahoney 2001; Clevenger *et al*. 2003; Aresco 2005*b*). The number of cars, large size of the road, and barriers between lanes may make it very challenging for a relatively slow-moving animal to cross unharmed. Our spatial model identifies dual carriageways such as the Hume Highway as having higher *C. longicollis* mortality. The Hume Highway is one of the major arteries within the Murray Catchment, crossing several major rivers and tributaries to the Murray, including the Murrumbidgee, Ovens, Broken, and Goulburn Rivers. The Hume Highway also crosses areas with high concentrations of lakes and farm dams, which may contain high densities of turtles. We also observed a higher likelihood of mortality on principal roads, which likely have greater traffic volumes than minor and rural roads in the countryside. Many urban centres also occur on or near the major rivers in the region, and so may be close to turtle populations.

We attempted to correct for potential spatial biases of the citizen scientists' observations by employing three different techniques: two bias layer additions (restricted background, point density), and thinning the data (Phillips *et al*. 2009;

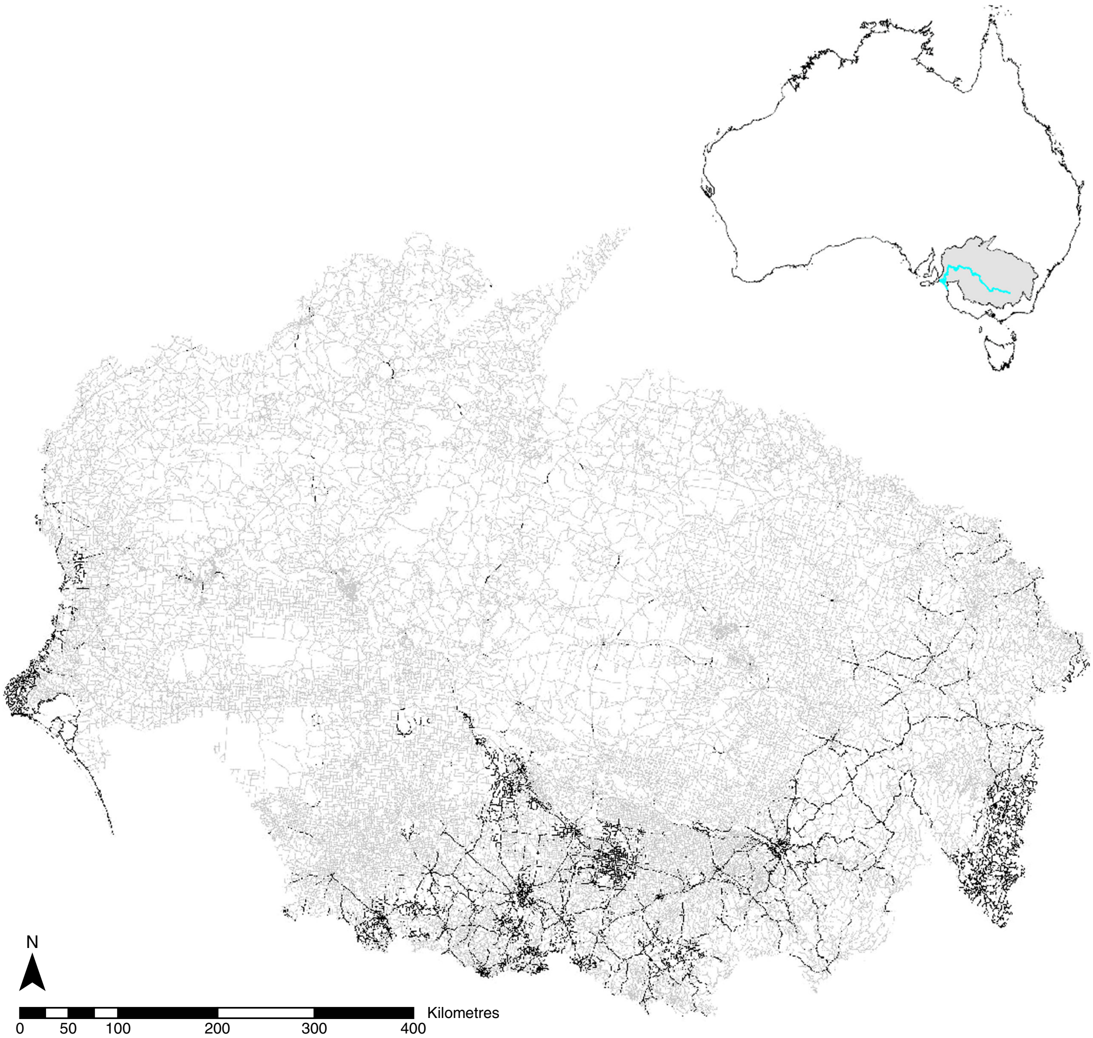

Fig. 3. Map of logistic output of *C. longicollis* model (restricted background). The 10 percentile training presence logistic threshold was used to create a binary suitability map (threshold = 0.09; above threshold, more likely road kill = black; below threshold, unlikely road kill = grey).

Kramer-Schadt *et al*. 2013; Fourcade *et al*. 2014). The addition of a restricted background was the most conservative technique. However, all corrected models yielded very similar results to the non-corrected one, which could be an indication that there is little spatial bias within the *C. longicollis* dataset. It is important to recognise that our models are limited by the absence of data on turtle population numbers or habitat suitability estimates, which, if included, would improve our predictions. Yet, our study is an example of a citizen science project allowing us to draw important conclusions about turtle road mortality.

Turtles are among the most threatened vertebrate taxa worldwide (Buhlmann *et al*. 2009). The potential of road mortality to drive turtle declines has been suggested from various sites in North America and Australia, and it requires mitigation (Aresco 2005*a*; Steen *et al*. 2006; Baxter-Gilbert *et al*. 2015; Spencer *et al*. 2017). Our data support this assertion, and the frequency of road mortality of freshwater turtles within the Murray River Catchment requires mitigation, particularly for *C. longicollis*. Our observations suggest that road mortality is highest during the nesting seasons, and principally in November for *C. longicollis*. Road warning signs placed in mortality hotspots temporarily during the spring and summer months may be good management solutions. Moreover, our results suggest that roads with high traffic volumes such as the Hume Highway pose the greatest threat. Thus, mitigation measures such as fences (Aresco 2005*b*) and culverts or 'eco-passages' (Dodd *et al*. 2004; Kaye *et al*. 2005) along these roads might be the most effective solutions. Indeed, there are several successful examples of these techniques. For instance, barriers that impede turtles to cross roads are effective for diamondback terrapins (*Malaclemys terrapin*) in New Jersey, USA (Ives-Dewey and Lewandowski 2012). However, these techniques may have limited effectiveness if not installed properly and with the biology of the target animals in mind, so sound design is of utmost importance (Baxter-Gilbert *et al*. 2015). Finally, creating artificial nesting habitats in between wetlands and roads, or alternative nesting sites such as 'nesting islands' (e.g. Wnek *et al*. 2013), may reduce the number of female turtles crossing roads. Evidence of freshwater turtles using nesting habitat of anthropogenic origin and artificial islands is available (e.g. *Clemmys guttata*: Beaudry *et al*. 2010; *Chrysemys picta*, *Chelydra serpentina* and *Emydoidea blandingii*: Paterson *et al*. 2013; *Malaclemys terrapin*: Wnek *et al*. 2013). Long-lasting barriers and eco-passages, paired with the creation of additional nesting grounds, could help curb road mortality of adult *C. longicollis*. As TurtleSAT is an ongoing project, and the dataset is continuously growing, it will be possible to gather more insights in the future. Currently, *C. longicollis* is in steep decline along the Murray River (Chessman 2011), and our study suggests that vehicle collisions could be a contributing factor to this decline. Road mortality surveys combined with population and demographic studies along major roads are therefore recommended to directly address this issue.

Conflicts of interest

The authors declare no conflicts of interest.

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