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RESEARCH ARTICLE

A shocking result—Electric fences protect western saw-shelled turtle (*Myuchelys bellii*) nests from depredation by foxes

Louise M. Streeting[1] | **Martin L. Dillon**[2] | **Jack Nesbitt**[3] | **Brad Nesbitt**[1,3] | **Lynn Baker**[3] | **Philip H. Spark**[4] | **Bruce C. Chessman**[5] | **Donald T. McKnight**[6] | **Paul G. McDonald**[1] | **Deborah S. Bower**[1]

[1]School of Environmental and Rural Science, University of New England, Armidale, New South Wales, Australia

[2]Northern Tablelands Local Land Services, Armidale, New South Wales, Australia

[3]Canines for Wildlife, Bellingen, New South Wales, Australia

[4]North West Ecological Services, Tamworth, New South Wales, Australia

[5]Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales (UNSW), Sydney, New South Wales, Australia

[6]Department of Environment and Genetics, School of Agriculture, Biomedicine and Environment, La Trobe University, Wodonga, Victoria, Australia

Correspondence
Louise M. Streeting, School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia.
Email: louisemstreeting@gmail.com

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Department of Climate Change, Energy, the Environment and Water, Australian Government; Department of Planning and Environment, New South Wales Government

Abstract

Introduced red foxes (*Vulpes vulpes*) are a major predator of freshwater turtle nests in Australia. We evaluated the effectiveness of electric fences, in combination with individual nest protection, for shielding western saw-shelled turtle (*Myuchelys bellii*: Chelidae) nests from predation by foxes. We compared the numbers of raided and intact turtle nests found in paired fenced treatment and unfenced control areas of streambank. We also individually protected all intact nests found in both area types with wire mesh or a steel cage. The total numbers of nests found in treatment and control areas did not significantly differ from parity, but significantly more intact nests were found in treatment areas and significantly more raided nests in control areas. The fences were occasionally damaged by livestock, wildlife and flooding, rendering them inoperative for varying periods of time until repair. However, foxes raided nests inside the fences on only two occasions, despite these breaks in functionality. Our study demonstrates that electric fences can provide an effective method of protecting entire nesting areas from depredation by foxes.

KEYWORDS
conservation, freshwater, nest protection, predator exclusion, turtle

INTRODUCTION

Modern extinctions are occurring at a rate that overshadows any previous extinction scenarios (McCallum, 2021), with turtles among the world's most imperilled vertebrates (Rhodin et al., 2021). Across the globe, turtle populations continue to decline despite decades of conservation effort (Lovich et al., 2018; Páez et al., 2015). In Australia, 8 of the 25 native freshwater

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turtle species recognized by the Australian Society of Herpetologists (2023) are currently listed as vulnerable, endangered or critically endangered under the federal *Environment Protection and Biodiversity Conservation Act 1999*.

The depredation of turtle nests by introduced predators is a key threat to the survival of many turtle species (Spencer, 2018). Introduced red foxes (*Vulpes vulpes*) prey on nests of Australian freshwater turtles and have a substantial impact on the recruitment of hatchling turtles (Chessman, 2022; Petrov et al., 2018; Thompson, 1983). Even very low numbers of foxes can depredate a high proportion of turtle nests, and fox densities must be reduced to near zero to significantly lessen nest predation rates (Spencer et al., 2017). In Australia, current fox control measures are unlikely to result in sufficient reduction or eradication of foxes to limit their impact (Saunders et al., 2010), and conservation strategies are urgently required to negate the impact of fox predation on turtle nests and consequent low recruitment rates.

The western saw-shelled turtle (*Myuchelys bellii*: Chelidae), also known as Bell's turtle, is an endangered Australian freshwater turtle endemic to high-elevation streams in the New England region of New South Wales and the Darling Downs region of Queensland (Chessman, 2015; Fielder et al., 2015). *Myuchelys bellii* have low annual fecundity (Fielder et al., 2014; Streeting et al., 2022) and delayed sexual maturity (Fielder et al., 2014). Predation of *M. bellii* nests by foxes is suspected to be high (Fielder et al., 2015), and populations are dominated by mature individuals with a low and potentially insufficient proportion of juveniles (Chessman, 2015). Conservation efforts for *M. bellii* include nest protection, artificial incubation of eggs and release of hatchlings (Streeting et al., 2022) and the use of electric fences to exclude foxes from nesting areas.

Previous studies indicate that electric fences can be a cost-effective approach for reducing depredation of freshwater turtle nests and may also reduce the frequency of monitoring required to locate and individually protect nests (Bennett et al., 2009; Geller, 2012). However, these studies used a limited range of fence designs and focused on North American turtles (*Malaclemys terrapin* and *Graptemys* spp.) whose primary nest predator is raccoons (*Procyon lotor*). We aimed to complement these studies by evaluating the effectiveness of a novel electric fence design and deployment for protecting turtle nests from foxes. Our fences were customized for riparian environments that frequently flood. The height, tension, spacing and voltage of our electrified lines and earth line were designed to target foxes while deterring livestock and wildlife such as eastern grey kangaroos (*Macropus giganteus*) and feral pigs (*Sus scrofa*). We also evaluated the effectiveness of individual nest protection both inside and outside the fences.

METHOD

Study locations

The study was conducted at sites on the Macdonald, Gwydir and Deepwater river systems in northern New South Wales supporting *M. bellii* populations. Sites (Figure 1) were selected using satellite imagery with follow-up field surveys to confirm the presence of *M. bellii* nesting activity. During three spring and summer *M. bellii* nesting seasons, fox-exclusion fences were deployed at up to nine sites (two sites in 2019–20, six sites in 2020–21, and nine sites in 2021–22). Each site consisted of a single fenced treatment area paired with an adjacent unfenced control area. The treatment and control areas at each site were equivalent in extent of potential nesting habitat (Figure 2). Both the treatment and the control areas were surveyed during each site visit. Site M1 was surveyed every 1–2 weeks each nesting

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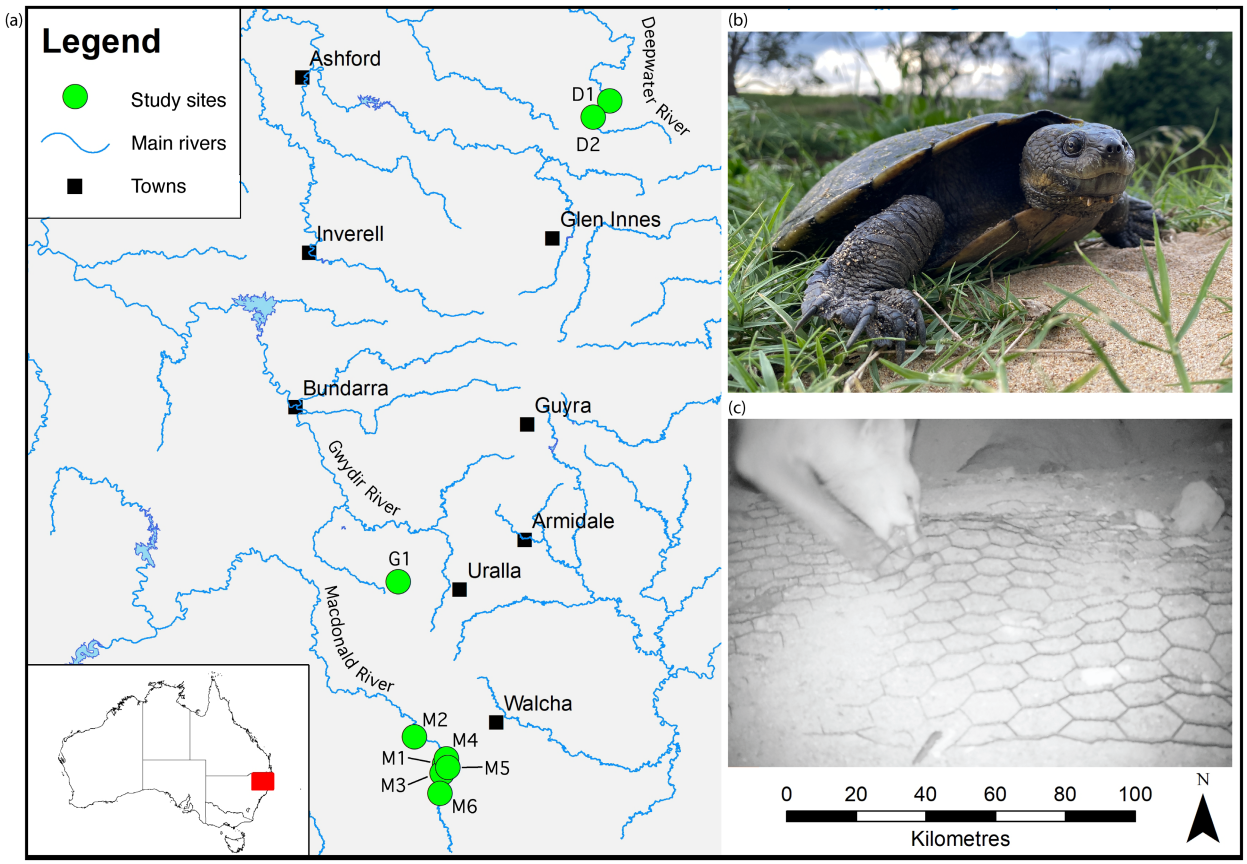


FIGURE 1 (a) Location of study sites (green dots) in northern New South Wales, Australia. Each dot represents a site comprising a fenced treatment area paired with an adjacent unfenced control area. Site identities are prefixed with letters indicating river systems as follows: D—Deepwater, G—Gwydir, M—Macdonald; (b) Adult female *Myuchelys bellii* (photo: Lou Streeting); (c) Trail camera image of a fox attempting to access a nest protected with wire mesh.

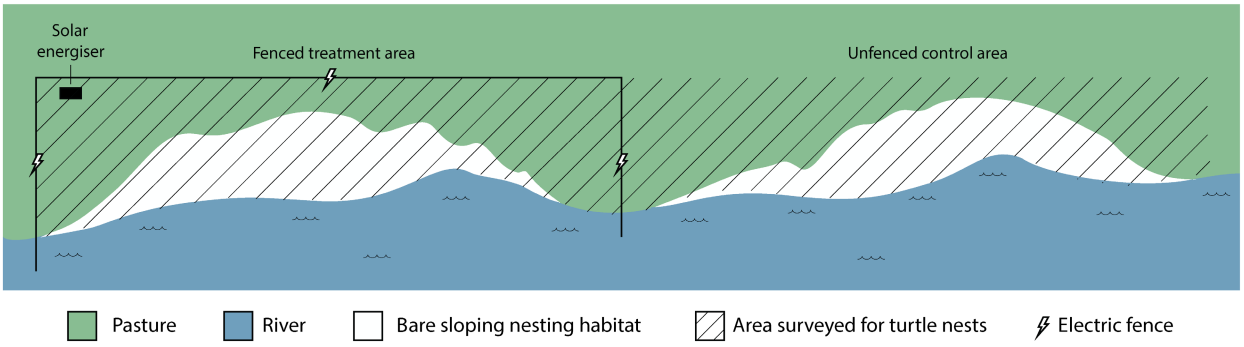


FIGURE 2 Diagrammatic representation of a typical experimental site comprising a fenced treatment area and an immediately adjacent unfenced control area, each containing an equivalent extent of potential nesting habitat (aerial view).

season. All other sites were surveyed 3–5 times each nesting season. Two other turtle species occur in the study area: the eastern snake-necked turtle *Chelodina longicollis* is present at all sites, while the Murray River turtle *Emydura macquarii* occurs only in the Deepwater River sites.

Electric fences

We installed and monitored a total of 17 temporary electric fences at nine nesting areas from 2019 to 2021. Fences were installed on site between

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mid-October and mid-November and dismantled the following autumn in March and April. They protected an area of streambank ranging from 47 to 334 m long and 10–30 m wide. The mean area protected by each fence was 0.2 ha (range 0.07–0.5 ha). The roughly rectangular treatment areas had electrified fencing on three sides. The ends of each fence either extended into the waterway or were placed at the top of a high vertical bank above a deep pool, to minimize the likelihood of foxes walking or wading around them. The fourth side of the treatment area was not fenced, but instead we relied on the river to deter entry from that side, as red foxes have been reported to be averse to swimming (Murie, 1959). Where necessary, before fence installation, pasture grasses and forbs along planned fence lines were slashed, mowed and/or treated with broad-spectrum herbicide (glyphosphate, 450 g/L) in a 1.5-m wide strip to reduce the likelihood of vegetation contacting the fence and potentially short-circuiting the system. Vegetation was periodically mowed, slashed or re-sprayed with herbicide as required throughout the study to prevent short-circuiting. During 2019–21, vegetation growth and management were minimal due to drought conditions, but from October 2021 wet spring and summer conditions stimulated excessive vegetation growth that needed regular maintenance along fence lines.

The fences were designed to deter foxes and livestock from accessing turtle nesting areas by imparting a non-lethal electric shock on contact. They were powered by Gallagher S100 solar energisers (Gallagher Group Limited) set to operate on half-power 'wildlife' mode to deliver a 4.5-kV shock with output energy up to 0.745 J throughout the day and night. The electric pulse interval ranged from 1 to 1.5 s depending on battery charge status. The Gallagher S100 specifications indicate that these energisers can power between 3000 and 10 000 m of multi-line fence depending on conditions. Fences consisted of five electrified braided strands (polywire) suspended from steel posts by plastic pinlock insulators. The bottom electrified line was placed 210 mm above the ground to minimize impacts on non-target fauna and allow the safe and unhindered passage of turtles, snakes, lizards and small mammals such as rakali (*Hydromys chrysogaster*) and echidna (*Tachyglossus aculeatus*). From October 2020 onwards, fences were constructed with four electrified polywire lines, with the lowest electrified line 210 mm above the ground and a single earth wire (steel or polywire) placed 100 mm above this (Figure 3a and 4). The earth wire was designed to ensure that a fox investigating the bottom wires of the fence received a strong electric shock when its head or body closed a circuit between one of the live lines and the earth wire. The earth wire was included to avoid reliance on the fox itself earthing the current, as an animal's fur has low conductivity and may act as insulation (Honda, 2022; McKillop & Sibly, 1988) and dry ground may not provide enough conductivity (Friedman, 2005). Fences were supported by 1.8-m steel posts ('star-pickets') set approximately 0.4 m into the ground at 8–12-m intervals. Steel or wooden braces were placed on the inside of the fences where necessary to support corner posts and to allow electric lines to be hand-tensioned. Plastic (non-conducting) spacers (multi-wire tread-in posts) were placed between steel posts where necessary to support the position and spacing of lines. Unlike Bennett et al. (2009) and Geller (2012), we did not place electrified baits on fences. We positioned the solar powered energisers facing north on posts inside the exclusion fences to protect them from curious cattle, but close enough to the fence to allow ready access for people to safely access the controls. Fences were fitted with 'electric fence' warning signs.

Where fences extended into the water, lines contacting the water were insulated from the rest of the fence to avoid short-circuiting. Where possible,

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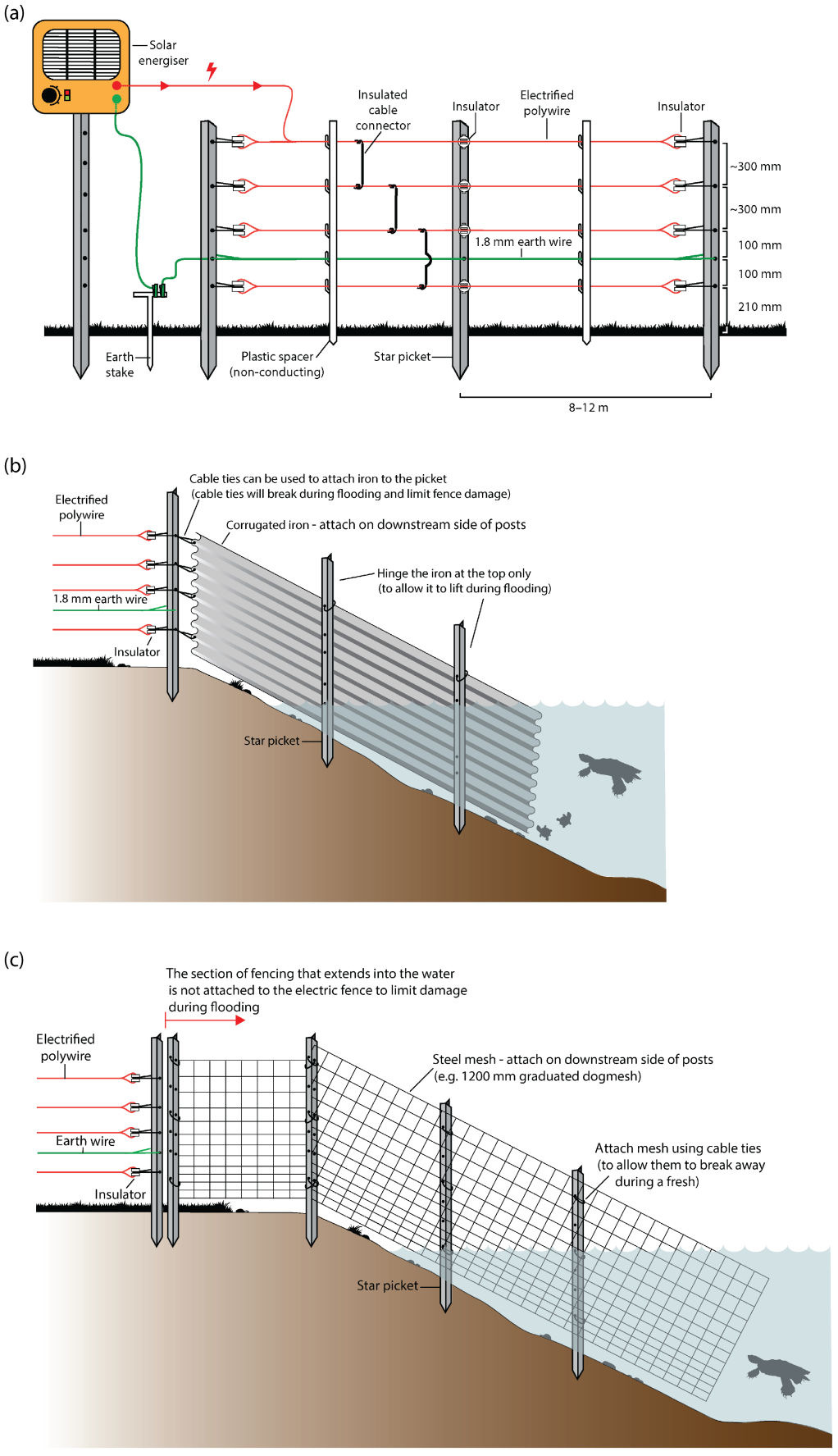


FIGURE 3 (a) Schematic diagram of electric fence; (b and c) Example designs for extending a fence into water. Illustrations adapted from Streeting et al. (2021).

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FIGURE 4 Site D2 electric fence with solar energiser and polywire lines.

the end of a fence entered the stream from a high bank, to minimize the length of fence exposed to potential flood damage and associated maintenance requirements. Where the end of a fence extended into the water, it was attached to either a sheet of corrugated iron (1800 mm long × 900 mm high) or steel mesh (1200 mm high × 2000 mm long) with graduated mesh size from 100 mm (top) to 50 mm (bottom) that were not electrified. The corrugated iron fence ends were designed to pivot with the water current in the event of temporary flooding or, for steel mesh ends, plastic cable tie attachment points allowed the distal end to break away from steel posts positioned in the river.

Locating nests

Prior to the study, in the spring and summer of 2017–18 and 2018–19, scent-detection dogs were deployed to aid in the identification of potential *M. bellii* nesting areas. The dogs were English springer spaniels from a working-dog line and were initially trained using urine and cloacal fluid odour from female *M. bellii*, and subsequently trained on live nests. The electric fences for this study were installed around likely nesting areas prior to the start of each turtle nesting season. Once the fences were installed, surveys for nests were conducted throughout the nesting season to locate live or raided nests within the fenced treatment areas or within the adjacent unfenced control areas. The electric fences were turned off while the dogs and their handlers surveyed the area. When a dog detected nest odour, it indicated the location by adopting a passive stance, or by dropping and placing its nose at the odour point. The dogs were also used at the end of each nesting season to locate hatched nests.

Nests were also located by searching along stream edges and visually examining the streambank up to 30 m from the water's edge for tracks and traces of turtle or fox activity such as disturbed soil and vegetation, turtle plastron impressions, turtle claw marks, excavations, eggshell fragments, turtle-nest exit holes and fox scats. Trail cameras (Campark T85) were installed at site M1, set on timelapse mode to take one 20-megapixel image per minute. A total of six cameras were placed on steel posts or wooden stakes at the tops of streambanks overlooking known and potential nesting areas. Camera images were reviewed weekly throughout each nesting season to record the timing and locations at which *M. bellii* emerged to nest (Figure 5). We categorized nests as either intact, raided or hatched, in the

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FIGURE 5 Trail camera image showing four *Myuchelys bellii* nesting simultaneously during a rain event.

last case as indicated by the presence of an exit hole and the presence of hatched eggshells in the nest chamber (Figure 6).

Data collection

Suspected intact nests were gently excavated to determine whether turtle eggs were present. If detected, eggs were left in situ, were not disturbed and were carefully re-covered with substrate. Eggshells from raided nests were removed to avoid recounting in subsequent surveys. Data collected for each nest included the date of detection, photographs of the nest and surrounding environment, spatial coordinates, groundcover, overhead vegetation, livestock (cattle and sheep) accessibility and evidence of predators such as tracks, scats or odour. If possible, nests were classified by turtle species according to the shape, orientation and diameter of the nesting chamber and the size and shape of eggs and eggshells. Exit holes were excavated with a hand trowel to confirm the presence of a nest chamber and hatched eggs.

Protection of individual nests with wire mesh

All intact nests detected before hatching in both treatment and control areas were protected with an overlying steel cage (500×500 mm, 50-mm mesh) or 800×800 mm piece of flat wire mesh (1-mm wire gauge, 50-mm hexagonal weave; Figures 7 and 8). The 50-mm spacing excluded predators but allowed hatchling passage, and no hatchlings were found constrained by nest protectors. The protectors were centred on the nest chamber and fixed with steel pegs hammered around their edges, taking care to keep pegs away from the chamber. Protectors were removed once hatchlings had emerged.

Statistical analysis

We tested three hypotheses: (1) The total number of nests (intact, raided and hatched) will be equal in treatment and control areas; (2) A higher proportion of intact nests will be found in treatment areas than in control areas; (3) A lower proportion of raided nests will be found in treatment areas than in control areas. We constructed three mixed-effects models

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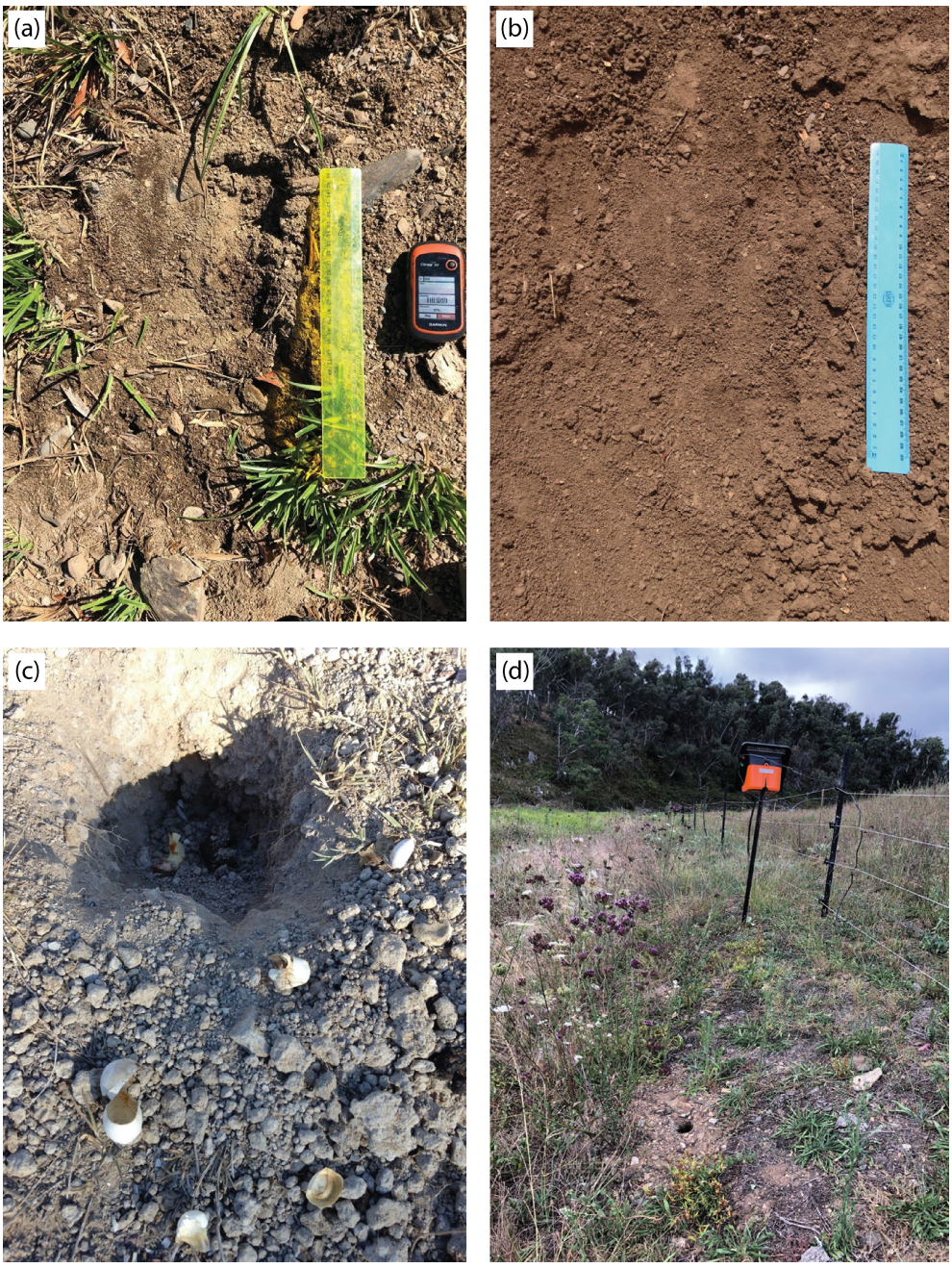


FIGURE 6 Examples of *Myuchelys bellii* nests: (a and b) Traces indicating a freshly laid intact nest (claw marks and plastron imprint), with 300-mm ruler; (c) nest depredated by a fox with scattered eggshells and a fox scat in the excavated nest chamber; (d) electric fence with an exit hole from a hatched nest in the foreground.

in R (ver. 3.5.0; R Core Team, 2018) using the package lme4 (ver. 1.1-15; Bates et al., 2015) to test these hypotheses. Each of the models included three fixed effects: a binary variable indicating whether nests were in a treatment or control area, the size in hectares of the treatment or control area and a categorical variable representing nesting season. Each model also included a categorical variable for study site as a random effect. We evaluated including study site nested within river, but this resulted in reduced model fit (evaluated with the Akaike Information Criterion) and often produced 'singular fit' warnings, and therefore we did not include river as a variable. The response variables for hypotheses 1–3 were, respectively, the total number of nests observed within each treatment or control area,

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FIGURE 7 *Myuchelys bellii* nest protected with wire mesh.



FIGURE 8 *Myuchelys bellii* nest protected with livestock- and fox-proof steel cage.

a binary variable indicating whether a nest was intact, and a binary variable indicating whether a nest had been depredated. Model i was a linear model, and models ii and iii were binomial models. For all models, we assessed the significance of comparisons using the Anova function in the car package (ver. 2.1-6; Fox & Weisberg, 2011) with Type II sums of squares and the Chi-square test statistic.

We did not statistically compare numbers of hatched nests between treatment and control areas because the application of individual nest protection would have confounded such a comparison. The number of intact nests that would have been depredated without individual protection was unknown.

RESULTS

Nest surveys

We recorded 129 nests over the three seasons (Table 1): 123 of *M. bellii*, three of *E. macquarii*, one of *C. longicollis*, and two of either *M. bellii* or *E. macquarii*. Of the nests detected, 58 had been preyed on before discovery, 49 were intact and individually protected from predators after discovery, and 22 had exit holes indicating hatching before discovery. All but one of the exit holes were inside treatment areas, the exception being 1.5 m outside the fence at site M4 in 2021–22. Nests could sometimes be detected for up to 2 weeks after laying based on known nesting dates recorded by trail cameras. Some raided and hatched nests were detectable for several

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TABLE 1 Numbers of turtle nests recorded within fenced treatment areas and unfenced control areas by nesting season. Each site consisted of a single fenced treatment area and an adjacent unfenced control area.

			Fenced treatment areas			Unfenced control areas		
Nesting season	Number of sites	Fenced area (ha)	Intact nests	Exit holes	Raided nests	Intact nests	Exit holes	Raided nests
2019–20	2	0.5	10	1	0	3	0	13
2020–21	6	1.1	17	7	8	2	0	19
2021–22	9	1.7	15	13	1	2	1	17
Totals	17	3.3	42	21	9	7	1	49

weeks before evidence disappeared. All intact nests protected with wire mesh ($n = 40$) or a steel cage ($n = 9$) avoided depredation (42 in treatment areas and seven in control areas). Camera records showed a fox biting and pulling on the mesh of a nest protected by wire mesh for 20 min before departing (Figure 1c).

The numbers of nests found in treatment areas ($n = 72$, 56%) and control areas ($n = 57$, 44%) were not significantly different ($\chi^2 = 1.0139$, $p = 0.3140$, df = 1), supporting hypothesis (1) and suggesting that, overall, the nesting habitat in the treatment areas was similar to that in the control areas. The total count of nests per site was positively correlated with the size of the nesting area ($\chi^2 = 43.947$, $p < 0.0001$, df = 1), but did not differ among nesting seasons ($\chi^2 = 4.3611$, $p = 0.1130$, df = 2).

The proportion of intact nests was significantly higher in treatment areas (42 of 72 nests, 58%) than in control areas (7 of 57 nests, 12%; $\chi^2 = 25.615$, $p < 0.0001$, df = 1), supporting hypothesis (2). The number of intact nests was not correlated with the size of the nesting area at each site ($\chi^2 = 0.0362$, $p = 0.3140$, df = 1) or with season ($\chi^2 = 2.7635$, $p = 0.2511$, df = 2).

The proportion of raided nests was significantly lower in treatment areas (9 of 72 nests, 12.5%) than in control areas (49 of 57 nests, 86%; $\chi^2 = 12.8469$, $p = 0.0003$, df = 1), supporting hypothesis (3). The number of raided nests that were found was not correlated with the size of the nesting area at each site ($\chi^2 = 2.1136$, $p = 0.1460$, df = 1) and did not differ among nesting seasons ($\chi^2 = 3.3801$, $p = 0.1845$, df = 2).

Causes of mortality

Of the 58 raided nests, 56 (97%) matched Thompson's (1983) description of nests robbed by foxes, having been raided and excavated to expose the bottom of the egg chamber, with empty eggshells scattered on the surrounding soil surface. Fox scats were found within or <1 m from 24 (41%) of the raided nests, and fox odour was detected at an additional raided nest. Throughout the entire study, no evidence of fox predation on adult turtles was recorded inside our treatment areas. However, in the 2021–22 nesting season the carcass of an adult *M. bellii* was found at a fox den 370 m upstream of site M5, and a fox was observed consuming a live adult *C. longicollis* outside of but adjacent to the fence at site D2. Another adult *C. longicollis* with all limbs consumed by a fox was found outside the fence and ~200 m downstream. We also located several fox foodcaches containing carrion including bovine bones and skin and the lower part of a kangaroo hind leg, indicating ongoing fox activity in the area. At site G1, intact *M. bellii* eggs from a nest raided in the unfenced control area were found cached 15 m away from the nest.

The electric fences did not exclude avian predators from the nesting areas, and images of corvids raiding *M. bellii* nests were recorded twice by

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trail cameras at site M1 in the 2019–20 nesting season. On one of those occasions, a corvid (likely *Corvus coronoides*) apparently frightened a nesting female *M. bellii* back into the water, leaving her eggs exposed in the uncovered nest chamber, and three corvids proceeded to consume the eggs. On the other occasion, images of corvids consuming *M. bellii* eggs on a nesting bank were recorded but it is unknown whether they excavated the nest or whether the eggs had been left exposed, perhaps by a turtle scared away in the process of laying, or perhaps due to a turtle excavating a nest chamber on top of an existing nest and scraping out the previous turtle's eggs. (On 18 November 2020, trailcamera images showed an *M. bellii* digging a nest at site M1 in the same location as a previous nest and scattering the previous nest's eggs on the surface of the soil.) In the 2019–20 nesting season, a landowner observed a white-bellied sea eagle (*Haliaeetus leucogaster*) in flight carrying a live adult female *M. bellii* and dropping it onto the ground a few hundred metres south-east of site M5, ~300 m from the river. The turtle survived the fall and began walking, but its subsequent fate was not observed. We found no evidence of predation by goannas (*Varanus* spp.), which leave widely dug-out nests lacking eggshells due to consumption of whole eggs (Thompson, 1983), nor did we observe goannas or their tracks.

Fox predation on nests inside the fences occurred only after they were damaged or rendered non-electrified by short circuits. For example, intermittent flooding damaged all nine fox-exclusion fences during the 2021–22 nesting season, and the fences were short-circuited and rendered non-functional for varying periods of up to 24 days until they were repaired. A fox destroyed one nest inside a flood-damaged fence at site M6 before 6 December 2022, and foxes destroyed eight nests inside the fence at site M3 after eastern grey kangaroos broke one of the plastic insulators, creating a gap in the fence and a short-circuit that rendered it ineffective for an unknown period between 3 November and 8 December 2020. However, nests located inside compromised fences were not always raided. Although the fence at site D2 was compromised by flooding in December 2021, an intact nest was found inside the treatment area a few metres away from a raided nest just outside. Additionally, a fox was observed inside the fence at site M1 on 14 March 2022, but no evidence of turtle nest predation was found.

DISCUSSION

Our models examining the proportion of nests raided by predators demonstrated that electric fences can augment individual nest protection to greatly improve the chance of *M. bellii* nest survival. Evidence of fence effectiveness was also provided by the number of nests that were not located until after they had hatched (i.e. exit holes) being much higher inside the fenced treatment areas. The use of electric fences around *M. bellii* nesting habitat reduces the likelihood of nest predation between site visits and significantly increases the number of nests that can be located while still intact and shielded further with individual nest protectors. Fences also facilitate detecting nests for individual protection by preserving visual signs of nesting that might otherwise be obscured by livestock and wildlife, such as tracks, claw marks, body/plastron imprints at the nest site and slide marks on the bank. Fencing over the entire nesting season covers critical periods immediately after laying and late in incubation when the signal strength of visual and olfactory cues used by mammalian predators to locate turtle nests is highest (Geller & Parker, 2022; Riley & Litzgus, 2014).

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In Australia, foxes are known to prey on adult turtles, including nesting females (Spencer, 2001; Thompson, 1983). We previously recorded the carcasses of five large female *M. bellii* and two adult female *C. longicollis* within a 10-m radius of an active fox den near site M1 (L.M. Streeting unpublished). An inguinal pocket of each *M. bellii* carcass had been accessed and eggshells were scattered around the carcasses. Female *M. bellii* have larger inguinal pockets and proportionally narrower plastrons than *C. longicollis*, which likely make it easier for foxes to access the eggs within the body cavity of *M. bellii*. During the present study, the ability of fences to protect nesting females was indicated by turtle carcasses being found only in the unfenced control areas. Protection of adult females is important because turtle populations are vulnerable to decline and extinction when subjected to even slight increases in adult mortality (Burke et al., 2000; Congdon et al., 1993; Heppell, 1998; Klemens & Thorbjarnarson, 1995; Páez et al., 2015).

Studies of turtle nest predation may be biased by differing detectability of intact and raided nests by human observers (Chessman, 2022). Raided nests are more visible and evident for a longer period than intact nests or exit holes, and exit holes are more visible and evident for longer than intact nests. The visibility of nests may also have varied between our treatment and control areas due to ground disturbance by livestock and wildlife outside of the fenced areas. However, our incorporation of multiple methods of nest detection—scent-detection dogs, visual surveys and camera traps—should have limited any overall detection bias.

The in situ protection of nests with individual predator-exclusion devices has long been used to improve the recruitment of threatened species, including turtles (Riley & Litzgus, 2013; Schindler et al., 2017; Standing et al., 2000). Our individual nest protection was 100% effective, even for nests that were located outside of the electric fences or inside fences that were breached by foxes. O'Connor et al. (2017) suggest that predator-exclusion devices may result in indirect and longer-term benefits because they alter predator-foraging behaviour over time by reinforcing the 'no-food-here' message. We suggest that individual nest protectors have the added advantage of preventing inadvertent excavation of existing nests by subsequent nesting turtles, and the steel cages also shield nests from trampling by livestock. However, individually protecting nests has a number of disadvantages. Some studies have found that predators can learn to associate protection structures with nests and target them (Bougie et al., 2020; Schindler et al., 2017). Cages and mesh may also reduce the amount of substrate available to other nesting females. Opportunities to pre-empt predators and individually protect nests can be limited by synchronous nesting triggered by seasonal cues such as rainfall, coupled with intensive nest predation soon after laying. The installation of temporary electric fences addresses this limitation by enabling more nests to be protected before predators are able to access them. Fences may prevent nest predation even without individual protection and therefore remove the labour-intensive task of searching for and protecting individual nests within the short window of time available to find nests before they are preyed on.

Mammals typically demonstrate avoidance learning in response to the presence of electric fences (McKillop & Sibly 1988) and Poole and McKillop (2002) found that most foxes avoid touching them more than once. While the physical barrier provided by electric fences is minimal, the negative stimulus of a shock provides a psychological barrier through behavioural conditioning (VerCauteren et al., 2006). Aversive behaviour means that electric fences can remain effective even during periods when there is no power (Minsky, 1980; Poole & McKillop, 2002). Our fences were subject to occasional damage by livestock, wildlife and flooding, rendering

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them inoperative for periods up to 24 days until repair. Despite these breaks in functionality, foxes raided nests inside the treatment fences on only two occasions. The three fence breaches that we recorded contrast with the 21 breaches reported by Geller (2012) at his two sites over three nesting seasons. Bennett et al. (2009) do not report the number of raccoon or fox breaches, but four of 10 nests within their seven treatment areas were depredated. Our electric fences effectively deterred foxes from *M. bellii* nesting areas, suggesting our design was fit for purpose.

As in Thompson's (1983) study investigating the predation of *E. macquarii* and *C. longicollis* nests, predation of nests at our study sites was readily attributable to foxes. Foxes are a small to medium-size canid with an adult shoulder height of 350–400 mm (Castelló, 2018). Our lowest lines were placed at 210 mm above the ground, approximately half the shoulder height of an adult fox, with an earth wire 100 mm above. Honda (2022) demonstrated that electric lines placed at approximately half the shoulder height of the target animal maximize the probability of the animal contacting the line. Our energiser produced a 4.5-kV shock that appears to have been effective in combination with the inclusion of an earth wire as one of the horizontal lines. The addition of earth wires increases the likelihood of delivering an electric shock to small mammalian predators when fences are energized with voltages >2.8 kV (Tsukada et al., 2019), and we maintained our fence lines at a relatively high tension which has been shown by Honda (2022) to be twice as likely to electrify animals as low-tensile fences. Our electric fence design was an efficient, effective and simple method for protecting *M. bellii* nesting areas from foxes.

Fences in riparian areas are vulnerable to flood damage. At our study sites, river levels can rise several metres during floods and our temporary fences were designed to have flood tolerance. Except for the ends, the fences ran parallel to the water, and where possible the ends of each fence ran down into the water from high banks to minimize the length of fence that was perpendicular to the direction of water flow. The polywire electric lines were primarily plastic with spiralling conductive metal threads running through them, and therefore had high elasticity. These electric lines could be hand-tensioned to be taught, but still had the flexibility to stretch when challenged by flood debris or animals. In contrast, permanent fences and wire and/or mesh electric fences are impractical in areas subject to periodic flooding. Our fence design proved both resistant and resilient to most flooding and provided protection for nesting areas with minimal maintenance requirements.

Myuchelys bellii nest on bare areas of streambanks, including livestock tracks and access ways (Streeting et al., 2021), where periodic grazing can help to prevent loss of nesting sites through incremental overgrowth of ground vegetation. However, grazing livestock may trample nests during the egg incubation period. To balance these two considerations, electric fences can be erected before the onset of nesting, left in place until eggs have hatched, and hatchling turtles have emerged, and then disassembled or completely removed to permit grazing. Incubating *M. bellii* eggs at lower temperatures extends incubation duration (Streeting et al., 2022) and therefore wet conditions and low temperatures will extend the period of time that fences are required.

While predator-exclusion fences have obvious benefits for the protected species, they can impact on non-target native species by disrupting movement and dispersal or by causing mortality through exposure or entanglement (Ferronato et al., 2014; Smith et al., 2020). In Africa, high-voltage electric fences designed to restrain dangerous wildlife can kill tortoises (Holt et al., 2021; Lee et al., 2021). The lowest electrified strand on our fences was 210 mm above the ground to allow smaller animals to pass

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underneath, particularly turtles and echidnas. We recommend that before erecting electric fences, any fauna likely to be present in the area should be considered, and fence line height, spacing, tension, voltage and pulse frequency should be adjusted accordingly to minimize the risk of injury or mortality to non-target species.

Implications for conservation management

Our study was part of the 'Turtles Forever' conservation programme for *M. bellii* (Streeting et al., 2022), and we individually protected every intact nest that we found. Our study demonstrated that in the absence of protection, a very high proportion of *M. bellii* nests is preyed on by foxes. Protecting individual nests with wire mesh or steel cages was 100% effective at preventing such predation, but synchronized nesting during rainfall events, rapid predation after nesting, and the inconspicuousness of intact nests mean that individual nest protection is impractical as a conservation action on a regional scale. The installation of temporary electric fences to exclude foxes from preferred nesting sites during the nesting season is more efficient and likely much more cost-effective than searching for and protecting individual nests, because the fences protect entire nesting areas and pre-empt predation. Electric fences also have the benefit of protecting nesting females and emergent hatchlings.

Depredation of nests inside our fenced treatment areas was recorded only during periods when the fences were compromised by short circuits due to flood damage or contact by wildlife. This finding suggests that if electric fences can be consistently maintained, individual nest protection might be forgone in fenced areas with acceptance of the resulting increased risk. Resources otherwise required for searching for and protecting individual nests could be diverted to installing and maintaining fences at additional sites or for the implementation of other conservation actions. We therefore advocate the use of standard agricultural electric fence systems with a simple design targeting foxes to provide a humane, safe, relatively flood-resistant and effective method for deterring or excluding foxes from *M. bellii* nesting areas.

Conservation practitioners are advised to carefully consider the time, labour and material costs involved in implementing alternative nest protection measures. The use of electric fences to safeguard nesting areas entails expenses for both materials and labour for fence installation, maintenance and disassembly. The frequency of flood events influences the time and labour required for fence maintenance. The main costs of installing individual nest protectors are the time and labour required to find nests before they are preyed on, which can be difficult and demanding.

Further research is required to quantify the detectability of nests, assess nest survival rates, understand the extent of predation on turtle nests and compare the cost-effectiveness of different methods for reinforcing freshwater turtle populations. While our study shows that electric fences work well in combination with individual nest protection, more research is needed to evaluate the efficacy of electric fences as a standalone measure. Population monitoring to determine hatchling survival through to maturity will be essential to evaluate the benefits of nest protection in the longer term.

AUTHOR CONTRIBUTIONS

Brad Nesbitt: Data curation (supporting); investigation (equal); methodology (supporting); resources (equal); writing – review and editing (equal). **Bruce**

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Chessman: Formal analysis (supporting); writing – review and editing (equal). **Jack Nesbitt:** Data curation (supporting); investigation (equal); methodology (supporting); resources (equal); writing – review and editing (equal). **Donald McKnight:** Formal analysis (supporting); methodology (supporting); software (equal); supervision (equal); writing – review and editing (equal). **Deborah Bower:** Investigation (equal); resources (equal); supervision (equal); writing – review and editing (equal). **Louise Streeting:** Conceptualization (equal); data curation (lead); formal analysis (lead); investigation (equal); methodology (lead); project administration (lead); resources (equal); software (equal); validation (lead); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Lynn Baker:** Data curation (supporting); investigation (equal); methodology (supporting); resources (equal); writing – review and editing (equal). **Martin Dillon:** Conceptualization (equal); data curation (supporting); formal analysis (supporting); funding acquisition (lead); investigation (equal); methodology (supporting); project administration (supporting); resources (equal); visualization (supporting); writing – review and editing (equal). **Paul McDonald:** Supervision (equal); writing – review and editing (equal). **Philip Spark:** Conceptualization (equal); data curation (supporting); investigation (equal); methodology (supporting); resources (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

We confirm that we have no conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the authors on reasonable request.

ORCID

Bruce C. Chessman https://orcid.org/0000-0002-4173-8023

TWITTER

Louise M. Streeting @lou_streeting

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