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Research

Simple fence modification increases land movement prospects for freshwater turtles on floodplains

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Installing conservation fences to prohibit feral animal access to wetlands can become a barrier for non-target species of interest. We collected 161 turtles (*Chelodina rugosa*, *Emydura subglobosa* worrelli, *Myuchelys latisternum*) from twenty floodplain and riverine wetlands during post-wet (June–August) and late-dry season (November–December) surveys (2015–2018) in northern Australia. Wetlands were fenced (150 × 150 mm square, 1.05 m high wire mesh) or unfenced around the wet perimeter. Ninety-seven percent of individuals caught in either fenced or unfenced wetlands had a shell carapace width greater than mesh width, of these 44 (46%) were captured inside fenced wetlands, while 50 were caught in unfenced wetlands. The remaining 35 turtles were smaller than 150 mm and would likely pass easily through fence mesh. Sixty-five turtles partook in a fencing manipulative experiment. Turtles with carapace widths wider than mesh often successfully escaped through fences by lifting one side of their shell and passing diagonally through the mesh. In a second experiment where a piece of vertical wire (1500 × 300 mm) was removed, turtles located 'gates' after prospecting and fitting through meshing areas that were too small to pass. Ninety-two percent of turtles were able to locate and pass through gates, while 8% failed to locate a gate after 2 h. Gates applied every 4 m showed an 83% passage rate, every 2 m was 91%, and every 1 m was 100%. Combing field and manipulative experiments revealed that large turtles will prospect and move along a fence until they find suitable passage, which has important consequences when considering that gates could be easily retrofitted to existing sites, as well in new fencing programs, which has enormous positive conservation benefits for turtles in an already challenging and changing floodplain environment.

Keywords: connectivity, exclusion fences, feral pigs, floodplains, freshwater turtles, wetlands

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Introduction

Conservation fences have the specific objective to ameliorate threatening processes on individual species or sensitive ecosystem habitats (Woodroffe et al. 2014). While these fences have been successful in the intended purpose (Durant et al. 2015), they have negative indirect effects on non-target species (Loarie et al. 2009, Rey et al. 2012), resulting in an ongoing conservation dilemma for managers (Ferronato et al. 2014, Jakes et al. 2018). For example, fences disrupt dispersal processes, and increase mortality (via increased exposure to unfavourable conditions or predators; Spencer 2002). These impacts are greatest on vagile animals which have evolved behavioral life history traits that allow them to inhabit landscapes characterized by spatial and temporal variability, and are therefore susceptible to limited access to resources or responding to local pressures (e.g. predation, climate conditions). Conversely, with every conservation fence there exists the opportunity to evaluate the design efficacy, and implement supplementary modifications and improvements as part of a continual process of enhancement (Loarie et al. 2009).

Wetlands (palustrine and lacustrine) located on floodplains away from riverine channels support rich aquatic plant and fauna communities (Jiang et al. 2015, Canning and Waltham 2021). During high water levels in flood, interconnecting riverine channels create a network of waterbodies that persist permanently or in a temporary state (Datry et al. 2018, Shumilova et al. 2019). Aquatic organisms occupying wetlands face a shifting land-water margin, until connection is finally broken. This process results in wetlands supporting a non-random assortment of aquatic and semi-aquatic species (Arrington and Winemiller 2006, Pander et al. 2018). The duration, timing and frequency that off-channel wetlands sustain lateral connection to primary rivers is a determining factor in broader aquatic ecology and production (Hurd et al. 2016, Galib et al. 2018). In addition to connection, environmental conditions become important including water quality (Wallace et al. 2015, Godfrey et al. 2016, Waltham et al. 2020b), access to shelter to escape predation, and available food resources (Jardine et al. 2012). Managers are increasing efforts to restore wetland ecosystem values, though access to empirical data demonstrating success are limited, which becomes central when attempting to assess biodiversity return for the funding invested by government or private sector markets after implementing the action (Weinstein and Litvin 2016, Waltham et al. 2019).

Across northern Australia, feral pigs *Sus scrofa* contribute wide-scale negative impact on wetland vegetation assemblages, water quality, biological communities and wider ecological processes (Fordham et al. 2008, Krull et al. 2013). Feral pigs have an omnivorous diet including plant roots, bulbs and other below-ground vegetation throughout terrestrial and wetland areas (Ballari and Barrios-García 2014). This feeding strategy has a negative impact on wetland aquatic vegetation (Doupé et al. 2010, Waltham and Schaffer 2018), which gives rise to soil erosion, benthic sediment resuspension and reduced water clarity and eutrophication which is particularly critical late-dry season. Only a few studies have quantified the negative impacts that feral pigs have on floodplain wetlands (Mitchell and Mayer 1997, Doupe et al. 2009, Steward et al. 2018, Waltham and Schaffer 2018), limiting the ability of land managers to measure the benefits of feral pig destruction (Fordham et al. 2006), or indeed other large invasive species (Ens et al. 2017). Strategies focused on reducing or removing feral pigs from the landscape have been employed since their introduction to Australia (Fordham et al. 2006), including poison baiting, aerial shooting and trapping using specially constructed mesh cages (Ross et al. 2017). Attempts to exclude feral pigs have also include building exclusion fencing for conservation outcomes by directly limiting access to essential resources (Nordberg et al. 2019). The installation of fences around wetlands has only recently been examined in Australia (Doupe et al. 2009, Waltham and Schaffer 2018), with results suggesting that fences prevent non-target terrestrial fauna access which becomes particularly pertinent late-dry season when wetlands are regional water refugia points in the landscape. While small terrestrial species including birds, snakes and lizards can still access fenced wetlands (Ross et al. 2017, Waltham et al. 2020a), freshwater turtle movement may be reduced – the prospectus of land movement during critical lifecycle ecology times is hindered. To this end, the inherent problem of wildlife fencing needs further consideration and data (Jakes et al. 2018) that is also part of broader wildlife conservation and resource management strategies.

While freshwater turtles represent an obvious and charismatic species occupying freshwaters on many continent (Ennen et al. 2020), they are actually facing risk of extinction due to burgeoning landscape changes including fragmentation or habitat loss (Browne and Hecnar 2007, Krull et al. 2013), nest predation (Spencer 2002, Doody et al 2006), or changes in hydrology either through direct water extraction or regulation (Micheli-Campbell et al. 2017), and climate change (Fordham et al. 2014). These threats are also apparent in northern Australia, because of seasonal wetland complexes (Georges 1992) and will employ terrestrial locomotion to exploit ephemeral food supplies, lay eggs or escape drought. Accessing terrestrial prospects exposes turtles to new hazards such as desiccation and predation by other terrestrial fauna (Gibbs and Shriver 2002, Hamer et al. 2016). Freshwater turtles hold important cultural values, which has led to funding feral control programs to install fences to protect turtles (Fordham et al. 2014). Installing conservation fences is increasingly be used to abate feral pig damage in northern Australia (Waltham and Schaffer 2018). While some improvements in wetland conditions have been presented (Waltham and Schaffer 2021), there are still concerns that fencing poses concerns to turtle movement.

As part of a broader feral pig abatement partnership between government, indigenous community and research agencies (Ross et al. 2017), our aim here was to evaluate the potential effect that wetland exclusion fencing has on the population demographics of freshwater turtle species inhabiting floodplain and riverine wetland complexes in northern Australia. Specifically, we examined shell morphology in relation to fence dimension characteristics from turtle populations captured in fenced and unfenced wetlands to determine the proportion of individuals whose mobility prospects across the landscape would be restricted because of fencing. Extending on the field observations and previous studies which have shown that turtles will persist in their attempts to overcome barriers to movement between wetlands (Ferronato et al. 2014), we tested the application of simple 'turtle gates' on a commonly used exclusion fence design to increase turtle mitigation efforts. By examining the shell morphology of wild turtle populations where fences are known to be a conservation concern, in combination with an ecological field experiment, we aimed to identify understand the size distribution of freshwater turtles in a major river catchment in northern Australia where fences are being erected, and secondly examine the prospects of turtles to find and pass through fence modification points to increase movement opportunities.

Material and methods

Description of study system

We studied freshwater turtles occupying floodplain and riverine wetlands between 2015 and 2018 within the Archer River catchment, Cape York Peninsula, Queensland (Fig. 1). The headwaters rise in the McIlwraith range on the eastern side Cape York, where the river then flows and enters the western side of the Gulf of Carpentaria. The catchment area is 13 820 km^2, which includes approximately 4% (510 km^2) of wetland habitats, including estuarine mangroves, salt flats and saltmarshes, wet heath swamps, floodplain grass sedge, herb and tree *Melaleuca* spp. swamps, and riverine habitat. The lower catchment includes part of the Directory of Internationally Important Wetland network (i.e. nationally recognised status for conservation and cultural value) that extends along much of the eastern Gulf of Carpentaria, including the Archer Bay Aggregation, Northeast Karumba Plain Aggregation and Northern Holroyd Plain Aggregation. Two national parks are located within the catchment (KULLA (McIlwraith Range) National Park, and Oyala Thumotang National Park). Land use is predominately grazing.

Rainfall is tropical monsoonal, strongly seasonal with 90% of total annual rain occurring between November and February. Long term rainfall records for the catchment reveals highest wet season rainfall occurred in 1989/1999 (2515 mm), while the lowest was 1960/1961 (563.5 mm). Total antecedent rainfall for the wet season prior (Nov 2014–Feb 2015) to this research was 1081 mm, close to the 10th percentile for historical records. The wet season during the years prior to this study (2010–2015) were among the wettest on record, proximal to the 95th percentile. The low rainfall experienced may have contributed to short flood duration, and connection between wetlands and the Archer River.

Twenty wetlands were sampled including both floodplain and riverine wetlands that were not on the main flow channels, but rather on anabranches and flood channels that connect to the main river channel during high flow events (Waltham and Schaffer 2021). Wetlands in northern Australia have been damaged by pigs (and cattle to a lesser extent) for the past 160 years (Gongora et al. 2004, Lopez et al. 2014). In an effort to protect wetland ecosystem and cultural values from further pig damage on Cape York (north Queensland), local indigenous groups Kalan Enterprises, Aak Puul Ngangtam and partners have commenced a program of fencing wetlands to abate feral pig and cattle from accessing wetlands (Ross et al. 2017).

Field methods – fenced and unfenced wetlands

Freshwater turtles were captured using specialized circular (820 × 2500 mm) collapsible 'cathedral-style' traps (Hamann et al. 2008) baited with canned sardines in vegetable oil. Generally, two traps were deployed in ~1.5 m of water, spaced ~150 m apart, mid-to-late afternoon (15:00–17:00 h) and checked between 10:00 and 12:00 h the following day. In some wetlands and at certain times of the year, low water levels rendered cathedral traps impractical. In these instances, turtles were passively sampled with unbaited fyke nets (1 mm mesh, 0.5 m height, single wing panel span 10 m) set along the wetland margins. All traps were open and undisturbed overnight. Captured turtles were weighed, measured (following the morphometric codes in the Supporting information) and released back at the site of capture. In addition to trapping, fence perimeters were searched on foot for evidence of turtles either alive or dead trying to pilot through fences. If found, the morphometric data of turtles were recorded and added to the dataset.

Enchaining fences for turtle conservation

Experiment 1 – fence mesh sizes

Four replicated field arenas were constructed on a flat grassy bank adjacent to a wetland lagoon near Townsville, Queensland (Fig. 2A). Each arena (4 × 6 × 1 m [L × W × H]) was constructed using 180 cm star pickets to which we attached galvanized fencing (Southern Wire Griplock 80/90/15) identical to that used in feral pig management in the Archer River catchment. Fences were 90 cm high and composed of 2.50 mm wire with a standard 150 mm gap between vertical strands. Eight horizontal strands of wire create 7 mesh panels which are arrayed in a vertically increasing graduated mesh design (mesh area [L × W mm] 'large' = 2316 ± 81 cm^2; 'small' = 1540 ± 46 cm^2) (Supporting information). Generally, the smaller mesh size is used at the bottom of the fence to reinforce against the prospect of pigs digging under fences (Ross et al. 2017). We tested the passage rates of turtles through these fences oriented with both the small (normal) and large (up-side-down) mesh panels at the bottom.

Sixty-five turtles *Emydura macquarii kreftii* were captured from waterbodies in close proximity to the experimental arenas. For every replicate in each trial, one individual was placed in the centre of a testing arena underneath an

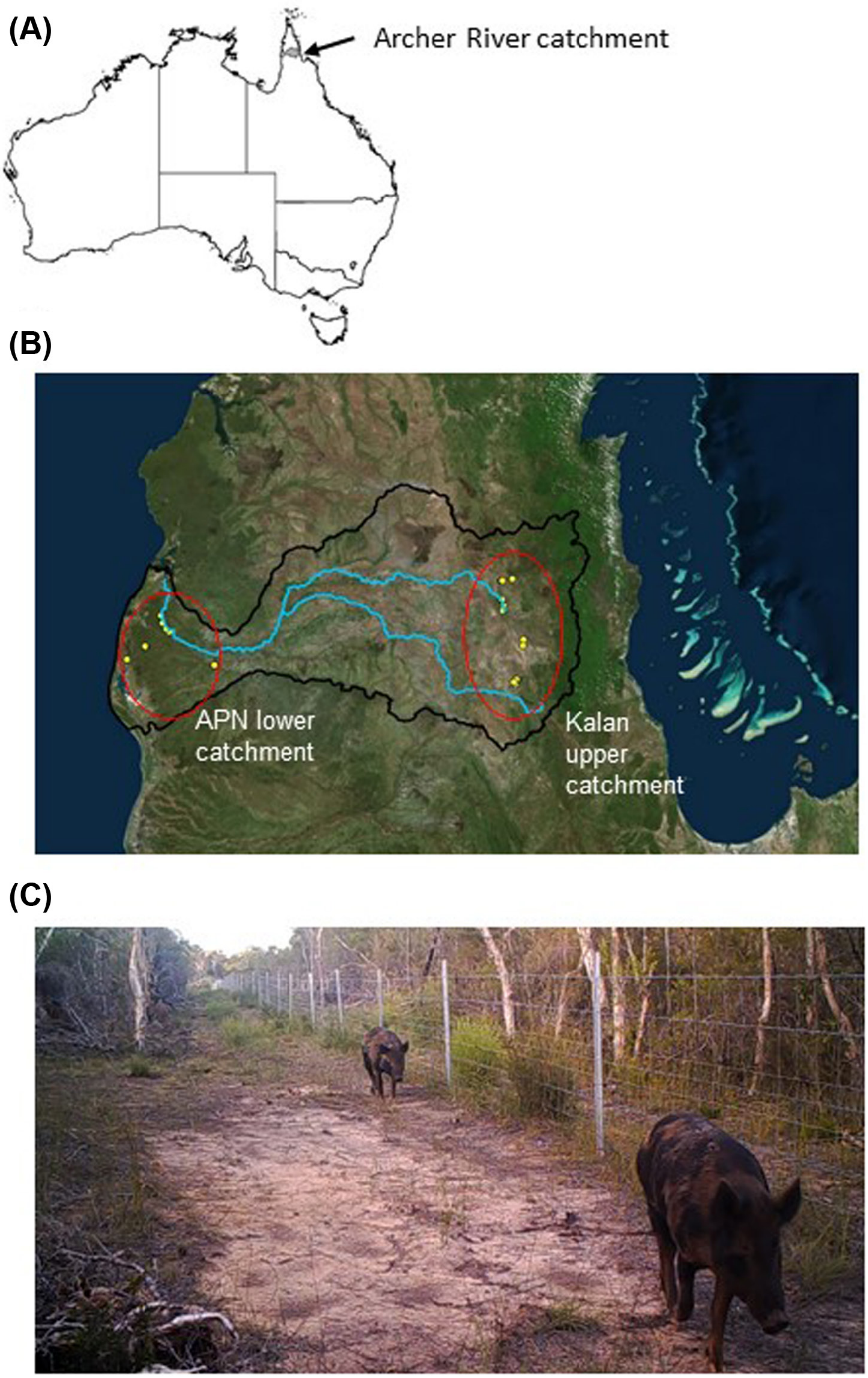


Figure 1. (A) Location of the Archer River catchment in northern Queensland, Australia, (B) wetland sites on the coastal floodplain and mid catchment where feral pig fencing has been completed around wetlands preventing access (yellow circles), (C) fenced wetland preventing pig access to coastal wetland (photo source S. Jackson, Queensland Parks and Wildlife Services).

upturned 70-l nally bin for 10 min to acclimate before being lifted for the trial to begin. To minimize disturbance, turtles were monitored via BluTooth GoPro video cameras attached and mounted to a suspended cross-beam overhanging each arena. Turtles were observed for up to 120 min to see if they could escape, after which the experiment ceased. After each trial, all turtles (including those that had escaped arenas) were kept in shaded, storage containers and released at the end of each day at the point of capture.

Experiment 2 – manipulated 'gate'

We designed a second experiment to test whether turtles could locate 'turtle gates' if they could not fit through the standard pig meshing. All field arenas were set up with the small mesh

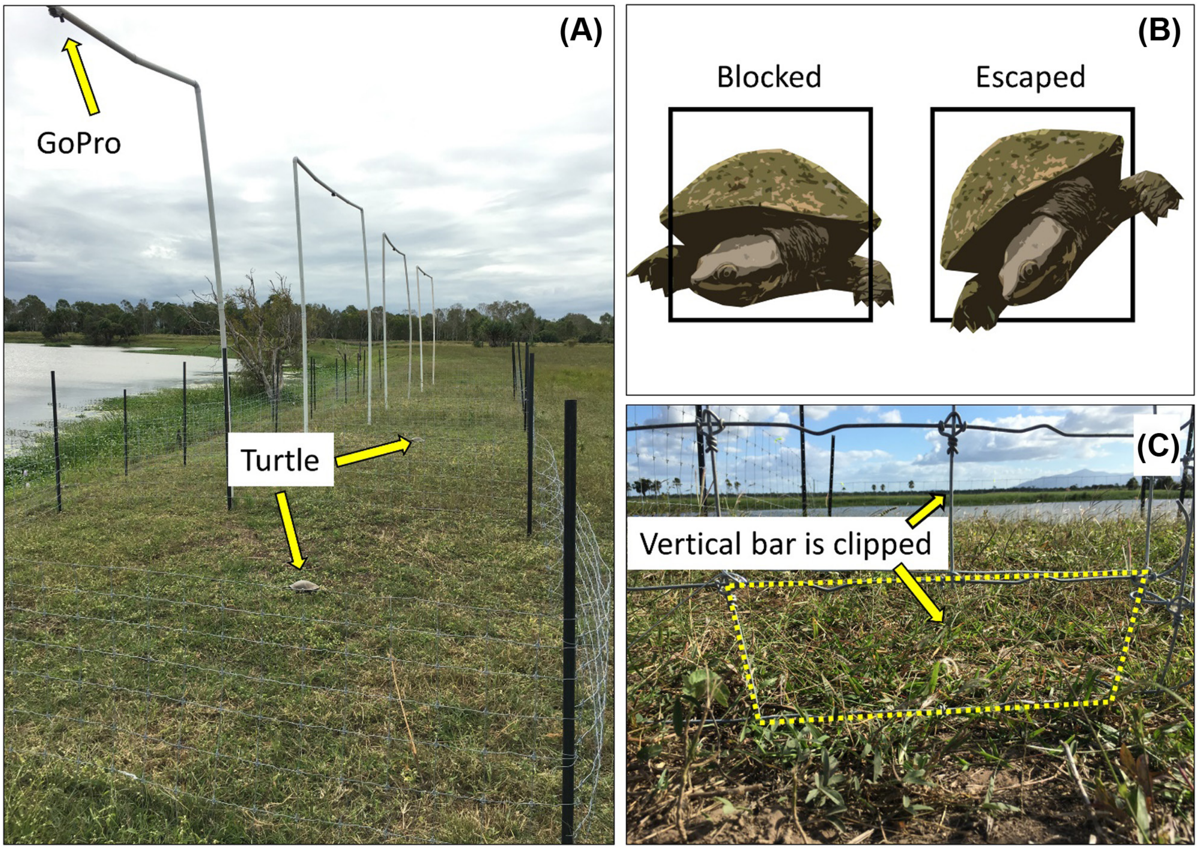


Figure 2. (A) Experiment 1 showing location of four replicate arenas used to measure turtle passage through fencing and to manipulate fencing gate design, (B) example of turtle blocked by fencing and escaped through fencing by angling body position, and (C) experiment 2 showing the creation of 'turtle gates' by manipulating the vertical bar of the first row of wire mesh to test efficacy of passage rates by turtles with new fencing design.

on the bottom, following construction protocols employed by ranger groups in northern Australia. An additional section of wire was weaved through the bottom row of wire meshing to ensure that turtles (44 *Emydura macquari krefftii* and one *Myuchelys latisternum*) would not be able to pass through the fence without using the turtle gates (ensuring turtles were blocked in arenas – Fig. 2B). This permitted the use of a wide range in body sizes (even those that would normally be able to pass through the small meshing). Turtles were placed into arenas with 'turtle gates' clipped into the bottom row of the fence. We examined if and how long it took turtles to locate and successfully pass through gates using three distinct treatments: field arenas with gates every 1, 2 and 4 m along the base. Each arena received the same gate spacing around the entire perimeter. The time it took turtles from release to exit through a gate after encountering a fence, and how far turtles travelled along the fence before existing the arena through a gate were recorded.

Data analysis

To examine whether turtle morphometrics differed between the Archer River floodplain (lower wetlands) to those captured in the upper catchment (upper wetlands), we used using multidimensional scaling ordinations, based on the Bray–Curtis similarities measure (Clarke 1993) with significance determined from 10 000 permutations. Multivariate dispersion were tested using PERMDISP, however, homogeneity of variance could not be stabilized with transformation, and therefore untransformed data were used. Multivariate differences using PERMANOVA (Anderson 2001) were tested using two factors: lower/upper wetlands (fixed), and fenced/unfenced (fixed).

Results

Archer River wetland field results

A total of 161 turtles were captured during this study, representing four species including *E. s. worrelli* (n = 96), *Chelodina rugosa* (n = 54), *M. latisternum* (n = 6) and *C. canni* (n = 5) (Supporting information). There were 79 females, 63 males, 14 juveniles and 1 sub-adult captured (with four where sex could not be resolved). In addition, three individuals were identified from in situ shell material found adjacent to wetlands in both the upper and lower catchment. One *C. canni* and one *E. s. worrelli* were identified from in situ shell

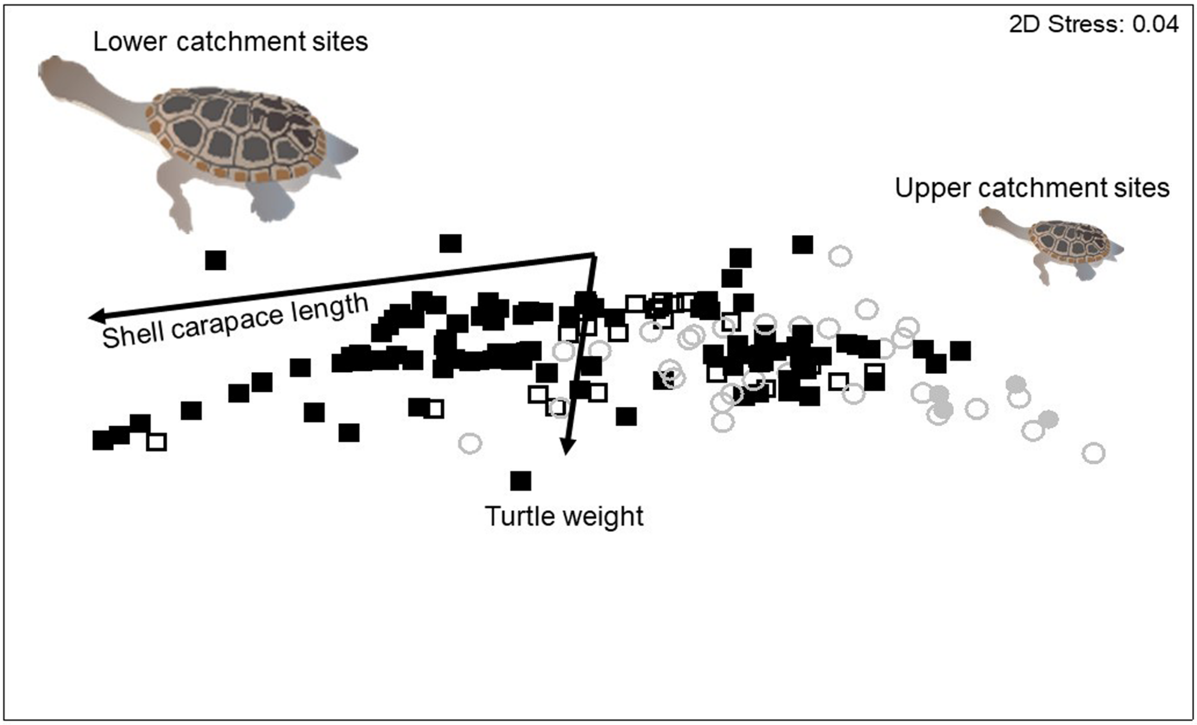


Figure 3. nMDS ordination of all individual turtles captured in the Archer River catchment during field surveys. Black boxes are turtles on the floodplain, grey circles are turtles from upper catchment – open symbols are fenced, and closed symbols are unfenced wetlands.

material found in the interior (not along the inside of the fence) of a fenced wetland in the upper catchment and one freshly pig predated, *C. rugosa* individual was found immediately adjacent to its aestivation site in an unfenced wetland located in the lower catchment.

The largest captured turtle was a female *C. rugosa* on the lower catchment floodplain, in an unfenced wetland (354.9 mm SCL, 245.9 mm SCW, 6.7 kg wet weight), while the smallest was an *E. s. worrelli* in a fenced wetland in the upper catchment (95 mm SCL, 87.5 mm SCW, 110 g wet weight). The average SCW (mean ± SD) for each species was: *E. s. worrelli* (147.7 ± 32.1 mm, n=96), followed by *C. rugosa* (160.7 ± 33.5 mm, n=54), *M. latisternum* (150.3 ± 29.3 mm, n=6) and *C. canni* (146.8 ± 30.1 mm, n=5).

There was an interaction between fencing/non-fencing and wetland region in the catchment owing to a difference in the turtle morphometrics between the lower and upper catchment wetland sites (PERMANOVA, interaction, pseudo-F=5.81, p=0.02; Fig. 3). However, some individuals from the unfenced lower catchment had turtles more similar to upper catchment fenced wetlands. Overall, turtles on the lower catchment floodplain were larger (in terms of shell width which is the main factor here) compared to those captured in the upper catchment (having smaller shell widths).

Pooling *C. rugosa*, *E. s. worrelli* and *M. latisternum* (161, 97% of total catch), 94 individuals caught in either fenced or unfenced wetlands that had a SCW greater than 150 mm, and would likely not be able to negotiate exclusion fences. (It is possible that with the diagonal width of mesh approximately 180 mm; see the Supporting information, turtles with a SCW slightly greater than 150 mm might squeeze through fence mesh though we could not confirm this at the time of field sampling and instead apply 150 mm SCW passable threshold to turtles – though see manipulative experiments below.) Of the turtles captured, 44 individuals (46%) were captured inside fenced wetlands, predominately *E. s.*

Table 1. Summary of turtles captured in fenced and unfenced wetlands on the lower floodplain and upper catchment flood areas. *C. canni* not included here given turtles were found on road crossings, not in wetlands.

			Unfenced		Fence	
Species	Location	n	<150 mm SCW	> 150 mm SCW	< 150 mm SCW	> 150 mm SCW
C. rugosa	Lower catchment	39	12	23	0	4
	Upper catchment	15	3	11	0	1
E. s. worrelli	Lower catchment	6	0	0	0	6
	Upper catchment	90	0	1	23	66
M. latisternum	Lower catchment	0	0	0	0	0
	Upper catchment	6	1	4	0	1

Table 2. Size distribution of turtles from experiment 1 – passage rates through feral pig fencing. Turtles were either blocked or escaped. Fence mesh size represents the size mesh at the bottom of the fence, closest to the ground (large = 150 × 150 mm; small = 150 × 100 mm). SCW = straight carapace width; SCL = straight carapace length; carapace height = max height from plastron to carapace. Range represents minimum–maximum.

Fence mesh size	Turtle outcome	n	Passage rate	SCW Mean ± SD (mm)	SCW Range (mm)	SCL Mean ± SD (mm)	SCL Range (mm)	Carapace height Mean ± SD (mm)	Carapace height Range (mm)
Large	Blocked	1	3.1%	173.6	173.6	232.7	232.7	94.4	94.4
Large	Escaped	31	96.8%	166.9 ± 15.0	139.5–205.8	218.3 ± 25.7	129.1–251.4	85.1 ± 10.1	59.7–101.0
Small	Blocked	7	21.2%	177.6 ± 6.5	170.0–187.6	234.7 ± 6.5	226.0–245.0	94.4 ± 3.8	89.7–100.2
Small	Escaped	26	78.7%	161.4 ± 13.9	121.4–184.5	210.8 ± 20.6	154.8–247.7	82.5 ± 9.5	63.2–100.0

worrelli (32, 34%), and most caught in the upper catchment (Table 1), while the remaining 50 individuals were caught in unfenced wetlands in the lower catchment (*C. rugosa*). The remaining turtles (35) were smaller than 150 mm and would be able to pass through fences.

Fence manipulative experiments

Experiment 1 – mesh sizes

Sixty-five turtles (n = 33 through small meshing; n = 32 through large meshing) were used in this feral pig fencing experiment (Table 2). When deployed with the small size mesh closest to the ground, 78.6% (26/33) of turtles were able to pass through without becoming stuck. In contrast, nearly all turtles (98.6%; 31/32) were able to pass through the pig fences with the large square meshing on the bottom (i.e. an up-side-down fence). Surprisingly, we also observed that even large turtles (with carapace widths wider than the meshing) were often able to escape through the fencing by lifting one side of their shell and passing through the mesh diagonally (Fig. 2B). This is the first evidence to suggest that the primary limiting dimension of the fence meshing is the diagonal width, rather than a horizontal width, as suggested by the field data which was unable to indicate whether we could not say if those individuals would pass through fences or not.

Experiment 2 – installing 'turtle gates'

Turtles located gates after prospecting and trying to fit through meshing areas that were too small to pass through. The majority (92.1%, 35/38) of turtles was able to locate and pass through gates, regardless of their spacing, while 7.9% (3/38 turtles) failed to locate a gate within 2 h (Table 3). For the three turtles that did not use gates, each appeared to have ceased attempts to pass through the mesh, dug into the grass, and remained motionless for the remainder of the trial. Gates applied every 4 m showed an 83.3% passage rate (10/12 turtles), every 2 m showed a 91.6% (11/12 turtles) passage rate, and turtle gates applied every 1 m showed a 100% passage rate (14/14 turtles). Turtles that used the gates spent less time searching for a passage through the fence when gates were closer together, with increased time searching with increasing distance between gates (Table 3).

Discussion

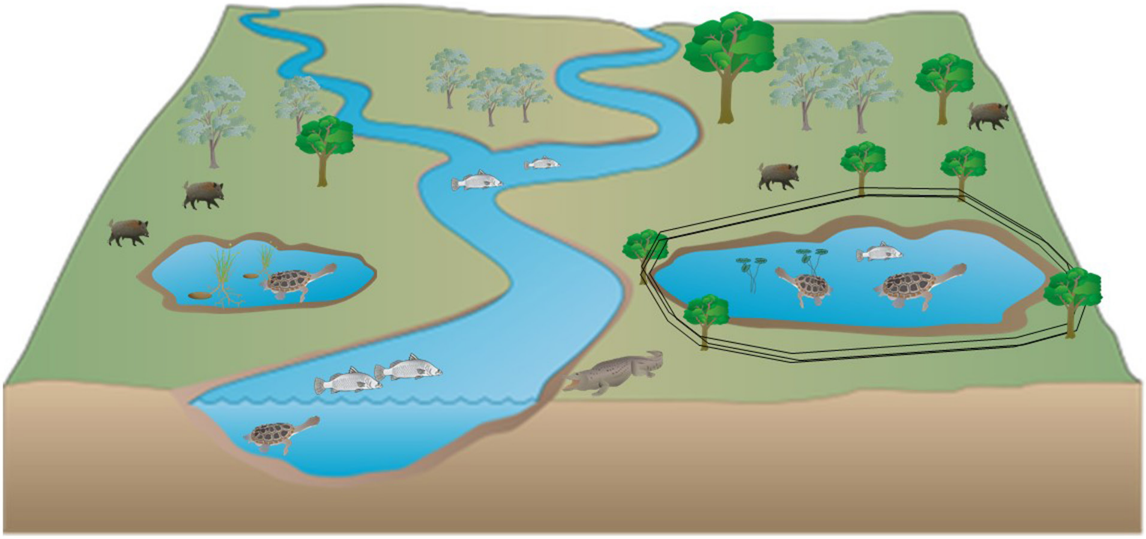
While the installation of fences to exclude pigs from wetlands and the periodic culling of pigs remain standard management strategies (Fordham et al. 2008), our field study shows that fences can be detrimental for turtle populations. However, this can now be overcome by incorporating modifications to fences to better assist freshwater turtle's passage that have a shell width greater than the dimensions of the fencing wire. The data here shows that turtles, regardless of species, with a shell width greater than the diagonal wire gap will likely be trapped inside (or outside) fenced wetlands, limiting their access to important resources including nesting sites, access to water, mates and food. The dilemma of reduced availability of freshwater turtle habitat can be mitigated by the simple and inexpensive design modification outline here, with turtles able to locate the gates and pass through them in a relatively short period, minimizing disruption to their overland movement activities.

Tropical wetlands can dry completely, especially when they are not close to main river channels or permanent lagoons (Waltham and Schaffer 2018). The rate of drying is dependent on antecedent wet season total rainfall, and the duration and frequency of floodplain connection (Wallace et al. 2015).

Table 3. Passage rates of 38 turtles in experiment 2 – testing if turtles locate and use 'turtle gates'. 'Fence to escape' represents the time turtles took to locate and use the turtle gate once they reached a fence. 'Distance travelled' represents the distance travelled once a turtle encountered a fence until it located a turtle gate, or the 2-hour time-cap elapsed.

Turtle gate spacing (m)	Turtle outcome	n	Passage rate	Fence to escape (min) Mean ± SD	Fence to escape (min) Range	Distance travelled (m) Mean ± SD	Distance travelled (m) Range
1	Used gate	14	100.0%	3.7 ± 8.5	0–33	2.0 ± 1.5	0.1–4.6
1	Blocked	0	0.0%	–	–	–	–
2	Used gate	11	91.6%	6.3 ± 12.7	0–43	1.9 ± 2.2	0–6.3
2	Blocked	1	8.4%	88	88	6.5	6.5
4	Used gate	10	83.3%	8.8 ± 10.6	0–36	2.1 ± 1.6	0–4.5
4	Blocked	2	16.7%	90.0 ± 12.7	81–99	2.2 ± 0.7	1.7–2.8

(A) Post wet season



(B) Dry season

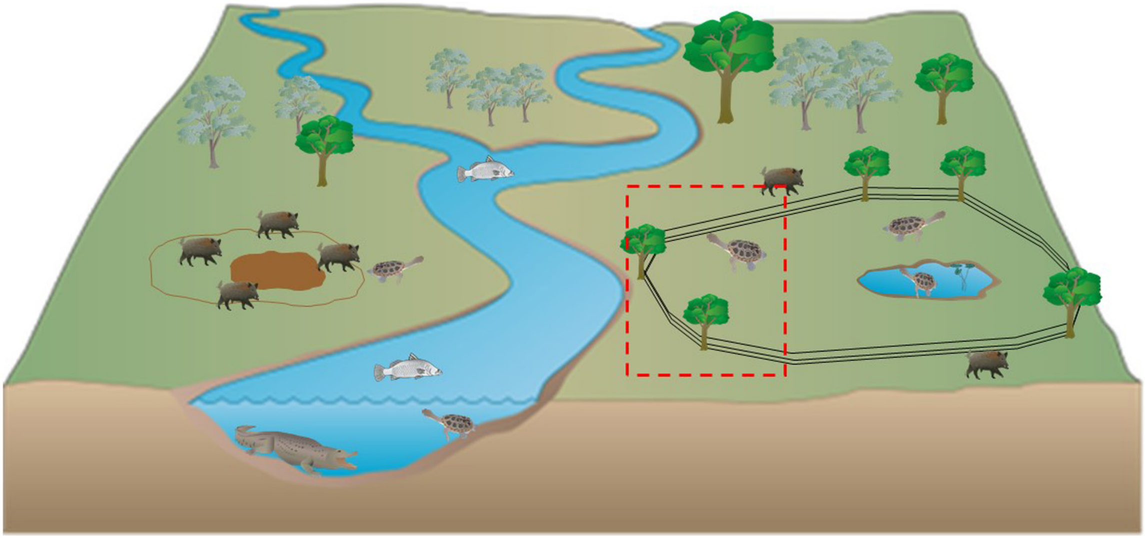


Figure 4. (A) Floodplain wetland complex following wet season and connection, (B) floodplain late dry season with drying wetlands and impact of feral pigs, red dashed line illustrates where gates should be installed to maximise turtle escape and return to primary river.

Therefore, in wet years, the presence of water remaining in fenced wetlands is more likely after the onset of the wet season, which may for some species (Supporting information) prohibit turtle overland dispersal to more permanent water. The wet season rainfall immediately prior, and during this survey, was within the 10th percentile for historical records, which resulted in some wetlands drying out, requiring turtles to migrate. In both cases, turtles are exposed to predation, either through pigs actively digging them up underground in unfenced wetlands (which was observed in this study), or during overland migration (by goannas, some bird species, wild dogs or pigs which are all predators of turtles, Spencer 2002).

Once erected, fence maintenance is imperative, particularly after bushfire, storm damage or flooding that cause damage and compromise fences (Kesch et al. 2015, Negus et al. 2019). Even after installing gates, surveys should continue to ensure that turtle movement throughout the landscape is not impeded by fences. Motion triggered cameras and passive transponder trackers (Soanes et al. 2015) could be installed at gates while routine inspections along fences (as part of general maintenance) ensuring that gates are in the most effective location. Further modifications could be administered retrospectively after gates are installed. Turtle gates may be strategically applied in travel corridors (Roe and Georges 2008) to minimize the need for large-scale clipping efforts around entire wetlands (Fig. 4) and would minimize the negative impacts on turtles by lowering energetic expenditure searching for a gate and reducing exposure to predation, overheating and desiccation.

The size separation in turtles between floodplain wetlands low in the catchment and riverine wetlands higher in the catchment was unexpected. This highlights important underlying differences in environmental conditions or food limitation contributing to turtle growth in the upper catchment remaining smaller compared to those on the expansive floodplain areas. This highlights the need to undertake extensive baseline surveys to understand local species morphology, as the inclusion of gate designs in wetland fences, even though inexpensive, might not be always necessary – which has the advantage of protecting fence integrity.

Implications for management

Each conservation fence program requires a scientific monitoring package to evaluate the efficacy, but more importantly to identify whether additional design improvements are necessary. We advocate here that an easy management response is to ensure the wider diagonal width squares are located along the ground when erecting fences, rather than the small diagonal width squares. This simple tactic increases the number of turtles that could pass through the fence without delay, and would conceivably not decrease the structural integrity of the fences to withstand pig prospecting, although, this should be empirically tested. However, simply removing a small piece of wire to increase openings allows for nearly 100% passage rates of turtles that would otherwise be stuck on one side of the fence. Turtle gates may be strategically applied in travel corridors to minimize the need for large-scale clipping efforts around entire wetlands. Further, gates can be easily retrofitted to existing fence designs, which has enormous positive conservation benefits for turtles in an already challenging, and changing floodplain environment.

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Author contributions

Nathan J. Waltham: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Funding acquisition (equal); Investigation (lead); Methodology (equal); Project administration (equal); Resources (lead); Supervision (lead); Visualization (lead); Writing – original draft (lead); Writing – review and editing (lead). **Jason Schaffer**: Investigation (supporting); Methodology (supporting); Writing – review and editing (supporting). **Sophie Walker**: Formal analysis (equal); Investigation (equal); Writing – review and editing (equal). **Justin Perry**: Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Writing – review and editing (equal). **Eric Nordberg**: Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – original draft (equal); Writing – review and editing (equal).

Data availability statement

Data are available from the Dryad Digital Repository: <http://dx.doi.org/10.5061/dryad.xsj3tx9h6> (Waltham et al. 2022).

Supporting information

The supporting information associated with this article is available from the online version.

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