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Effects of coastal development on sawfish movements and the need for marine animal crossing solutions

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Abstract

Although human-made barriers to animal movement are ubiquitous across many types of ecosystems, the science behind these barriers and how to ameliorate their effects lags far behind in marine environments compared with terrestrial and freshwater realms. Using juvenile sawfish in an Australian nursery habitat as a model system, we aimed to assess the effects of a major anthropogenic development on the movement behavior of coastal species. We compared catch rates and movement behavior (via acoustic telemetry) of juvenile green sawfish (*Pristis zijsron*) before and after a major coastal structure was built in an important nursery habitat. Acoustic tracking and catch data showed that the development did not affect levels of sawfish recruitment in the nursery, but it did constrain movements of juveniles moving throughout the nursery, demonstrating the reluctance of shoreline-associated species to travel around large or unfamiliar coastal structures. Given the current lack of information on human-made movement barriers in the marine environment, these findings highlight the need for further research in this area, and we propose the development of and experimentation with marine animal crossings as an important area of emerging research.

KEYWORDS
coastal highway, elasmobranch, shoreline development, threatened species, underpass

INTRODUCTION

Human infrastructure provides challenges and opportunities for many wild animal populations. An important consideration of human development is the fragmentation of landscapes, which can inhibit the movement and dispersal of many animals (and plants) or in some cases can enhance the dispersal and establishment of other taxa (Oxley et al., 1974). Adaptive management to minimize the effects of barriers is relatively well considered and advanced in some contexts. For instance, terrestrial faunal and floral migration corridors, including road and rail overpasses and underpasses, have received considerable scientific and engineering attention, leading to the development of minimum standards of statutory significance (de Medeiros et al., 2022). Similarly, fishway science and engineering in freshwater environments have developed over several decades in subsistence and heavily modernized regions (e.g., Lagarde et al., 2021; O'Connor et al., 2022). In contrast, anthropogenic barriers to movement are often not recognized in the marine environment; as a result, marine passage science is less well developed.

Globally, the nearshore environment has been heavily modified. Although hard-structure-associated marine species may benefit from some types of human developments (e.g., bivalves and rocky-bottom fishes inhabiting platforms, rock walls, and boat moorings; Bradley et al., 2023; Waltham & Sheaves, 2015), impacts on structure-negative species, including mobile and roving shallow-water species (e.g., sand inhabiting taxa), are easily overlooked and can be challenging to quantify (Baxter et al., 2023; Costa-Pierce, 2022). Furthermore, marine animal movement patterns and migrations along coastal routes can be critical for foraging, reproduction, and seeking refuge in many marine species, particularly large, highly mobile taxa. For example, productive river mouths, deltas, mangrove systems, and tidal creeks represent important pupping sites and nursery areas for many elasmobranchs (Heupel et al., 2007; Leurs et al., 2023; Martins et al., 2018). However, such productive coastal areas are also often prime targets for human development (Brown et al., 2018; Halpern et al., 2008). Thus, it is essential to consider near-shore habitat use and migration corridors of resident species when planning and coordinating nearshore developments (Cole et al., 2023; Waltham & Sheaves, 2015), although a lack of knowledge of how nearshore animals interact with developments can hinder this process (Bishop et al., 2017).

We aimed to empirically assess the effects of a major anthropogenic development, in this case a large piling jetty, rock wall harbor, and dredged shipping lanes associated with a gas processing plant, on the nursery use and movement behavior of a coastally associated species. We used green sawfish (*Pristis zijsron*) inhabiting a globally important nursery in remote northwestern Australia (Morgan et al., 2015) as a model species for this investigation. Green sawfish are recognized as critically endangered globally by the International Union for Conservation of Nature (Harry et al., 2022), and the nearshore delta of the Ashburton River in Western Australia is essential habitat for some of the last robust populations of this species (Harry et al., 2022; Morgan et al., 2017). Specifically, we sought to determine whether recruitment of pups to the region and the use of nearshore habitat by juveniles were affected by the installation of coastal infrastructure.

METHODS

All work with animals was conducted under Murdoch University Animal Ethics permits RW3191-19 and RW2397/11, Department of Environment and Conservation SF007889 and Department of Fisheries permits 3378, 250922121, and Regulation 178 (2011–2012).

Study site

This study was conducted in the Ashburton River and nearby tidal creeks and lagoons in the Pilbara region of Western Australia (Figure 1). The Ashburton River delta and adjacent tidal creeks are characterized by mud or sand flats often lined with mangroves. The Ashburton River delta and adjacent area were first identified as a nursery for green sawfish in 2011 (Morgan et al., 2015). Individuals typically stay in their primary nursery (near their pupping location) for approximately a year before expanding their range into nearby areas (their secondary nursery) as they grow, leaving the wider nursery area once they reach approximately 3000 mm in total length (TL) (Morgan et al., 2017).

The first stage of this study (2011–2013) was conducted prior to major developments in the vicinity of the Ashburton River (Figure 1). In 2014–2017, the Chevron Australia Wheatstone Plant and its associated product loading facility (PLF) and material offloading facility (MOF) were constructed approximately 9 km east of the Ashburton River mouth. The PLF consists of a large piling jetty stretching approximately 1 km from the high tide mark (Figure 1). The MOF consists of a solid rock wall reaching approximately 500 m offshore from the high tide mark and bending around to create a safe harbor for pilot vessels and offloading of materials (Figure 1). Both facilities are associated with dredged channels to accommodate large shipping vessels. The second stage of this study (2019–2022) was conducted after these facilities were in full operation. During the predevelopment phase, boat traffic in the study area was mostly limited to occasional small recreational vessels, whereas during the postdevelopment phase boat traffic from large and small vessels was common daily, including approximately 4–5 LNG tankers (~300 m) loaded from the PLF every week.

Sawfish capture and tagging

Green sawfish were captured in the Ashburton River mouth (−21.69 S, 114.92 E), Hooley Creek (−21.68 S, 115.03 E), and Four Mile Creek (−21.68 S, 115.06 E) (Figure 1) in 2011 and again in 2019–2021 for tagging purposes. In 2019–2021, sawfish were also captured in an additional Ashburton delta site (Hooley Lagoon, −21.68 S, 114.99 E), directly to the west of the PLF/MOF (Figure 1). In both stages of the study, sampling occurred roughly twice per year in spring (October–November) and autumn (April–May). Sawfish were captured using cast nets or 150-mm stretched-mesh monofilament gill nets approximately 60-m long set perpendicular to the shoreline and typically fishing shallow areas <2 m in depth. Once set, nets were monitored and checked when activity was observed or at least once per hour.

When sawfish were captured, they were removed from the net, sexed, and measured for TL. In males, maturity status was noted through clasper morphology. Following measurements, external identification tags were attached just below the first dorsal fin: Rototags (Dalton ID System) in 2011 and T-bar (model TBF) or spaghetti tags (model PDAT) (depending on the size of the individual) in 2019–2021 (Hallprint Fish Tags). Finally, sawfish were tagged with model V13 coded acoustic transmitters (Innovasea) that measured depth and temperature (estimated transmitter life 514 days predevelopment, 652 days postdevelopment). Alternatively, a few individuals tagged in 2020 had V13 transmitters that measured depth and body acceleration instead (estimated transmitter life 386 days). In 2011, acoustic transmitters were paired with Rototags and externally attached to the first dorsal fin with methods described by Morgan et al. (2017). In 2019–2021, acoustic transmitters were surgically implanted in the body cavity of the fish by making an ~2-cm incision on the ventral side, inserting the tag, and closing the incision with 2–3 stitches of 4/0 dissolvable sutures (Q315; MONO Q). Once tagged, sawfish were released at the site of capture.

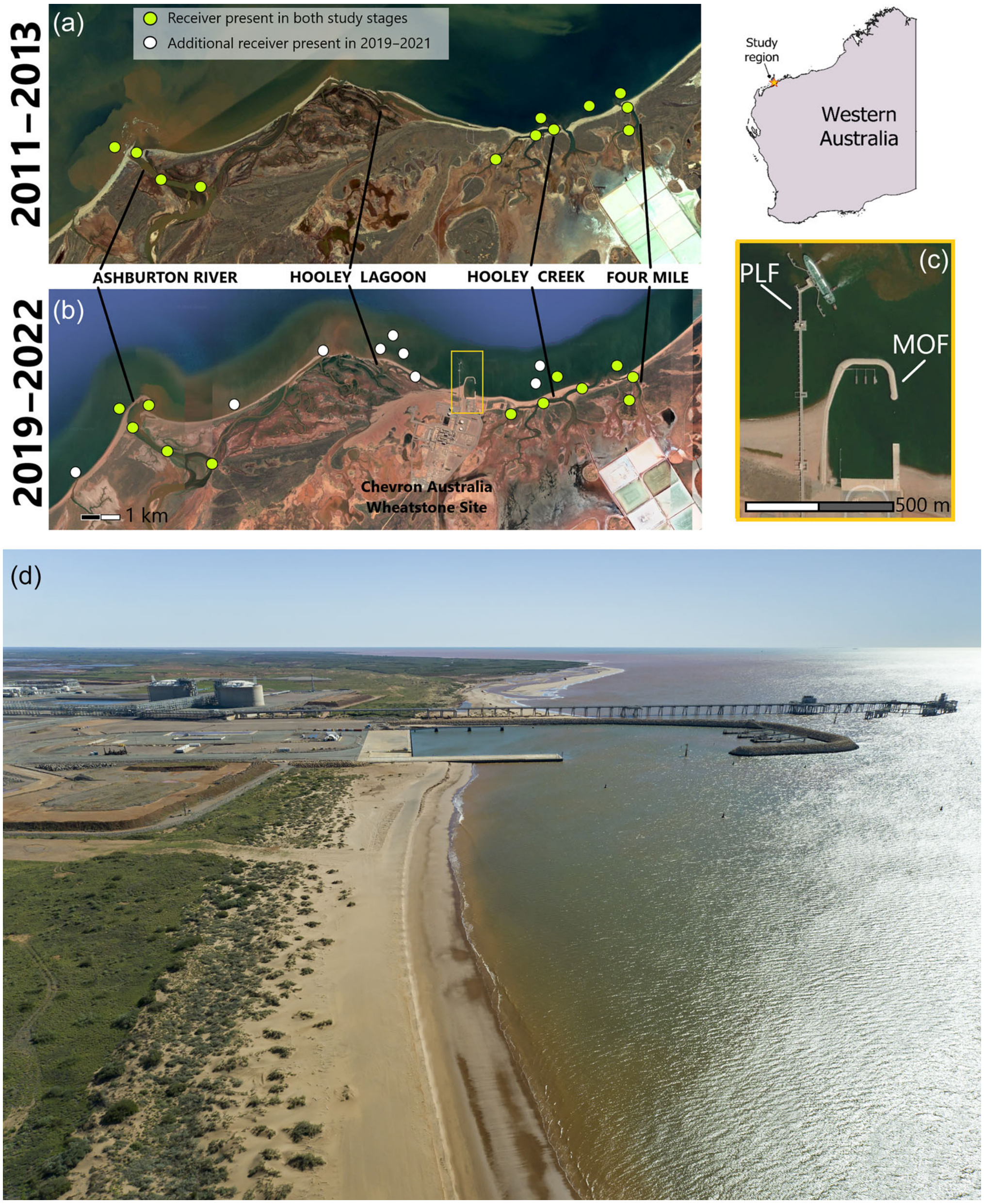

FIGURE 1 Ashburton River and nearby tidal creeks and lagoons in the Pilbara region of Western Australia: (a) region and receiver array in 2011–2013; (b) region and receiver array in 2019–2022 after development of the Wheatstone gas plant; (c) product loading facility (PLF) and material offloading facility (MOF) in the middle of the study area (yellow box in panel [b]), and (d) the MOF, PLF, and Wheatstone plant along the shoreline. Images in panels (a–c) captured from Google Earth. Photograph in panel (d) by Andrew Slater.

Acoustic monitoring

Transmissions from tagged sawfish were monitored with an array of VR2W acoustic receivers (Innovasea). In 2011–2013, 12 acoustic receivers were deployed on surface moorings within the Ashburton River, Hooley Creek, and Four Mile Creek, as well as directly offshore of all 3 systems (Figure 1). In 2019–2022, receivers were redeployed at roughly these same locations, by which time the geomorphology of the mouths of some systems had changed substantially and receiver locations were adjusted accordingly. In 2019–2022, 10 additional receivers were deployed throughout the array to gain a better understanding of space use, particularly surrounding the new developments (Figure 1), although no receivers were placed directly under or next to the new developments due to access restrictions. Receivers had nonoverlapping detection ranges with sometimes substantial space between receivers (up to 12 km predevelopment and up to 3 km postdevelopment); therefore, receiver coverage within the study area was not complete. Receiver range testing conducted in 2011 indicated that receivers had approximately 250–300 m of detection range; thus, a conservative detection range of 250 m was assumed for all receivers during spatial analyses. All receivers were downloaded semiannually throughout each study period.

Data analyses

Acoustic receiver data were initially processed in VUE 2.6 (Innovasea), and further statistical analyses were performed in R (R Core Team, 2022). To examine whether the development of the PLF and MOF affected the population dynamics and movement patterns of sawfish, several parameters were compared between pre- and postdevelopment periods. These included the catch per unit effort (CPUE) of sawfish in the Ashburton River, Hooley Creek, and Four Mile Creek, space utilization, and residency of sawfish and the tendency of sawfish to transit through the PLF and MOF areas, described in following paragraphs. Because size class affects movement patterns of juvenile green sawfish in this area (Morgan et al., 2017), sawfish were split into different size classes for several of these analyses, including young of year (YOY) individuals (<1000 mm TL), young juveniles (1000–2000 mm TL, ~1–3 years old), older juveniles (2000–2500 mm TL, ~3–5 years old), and subadults (>2500 mm TL, ~>5 years old) (Lear et al., 2023). These size splits were determined from natural breakpoints in the data and apparent breakpoints in movement characteristics of sawfish (Morgan et al., 2017).

A series of linear and zero-inflated models were used to assess potential effects of the development on various aspects of sawfish recruitment and movement. For all of these models, collinearity of predictors was assessed using the variance inflation factor in the car package in R (Fox et al., 2012). Other model-specific assumptions, including normality of residuals and homoscedasticity, were checked using diagnostic plots in R for each best-fit model.

CPUE was calculated as the number of individual sawfish caught per 20 m of net per hour. Overall CPUE was quantified for all sawfish caught, and CPUE of specific life stages was also examined by calculating CPUE for exclusively YOY sawfish and for exclusively age 1+ sawfish (all sawfish excluding YOY) in each fishing area during each sampling trip. The CPUE was compared between pre- and postdevelopment periods with a series of linear models, which predicted CPUE for each age class of sawfish by study period (pre- and postdevelopment), time of sampling (autumn vs. spring), and sampling location (Ashburton River, Hooley Creek, and Four Mile Creek). A set of models with all combinations of predictor variables and interactions between predictors was created using the dredge function in the MuMIn package (Bartoń, 2020) in R, and the best-fit model was selected through a combination of parsimony and Akaike's information criterion corrected for small sample size (AICc), with predictor variables maintained in the best-fit model taken as influential predictors of CPUE.

For each sawfish transmitter deployment, the length of the deployment, here termed *transmission period* (defined as number of days between the first and last detection), was calculated, as was residency of the sawfish to the whole receiver array and to their specific tagging location. Residency was calculated as the number of days the sawfish was detected within an area (either the whole array or the specific tagging location) as a proportion of the transmission period. Patterns in residency to the tagging location of each individual were evaluated by building a series of linear mixed-effect models in the lme4 package (Bates et al., 2015) in R, where residency to tagging location was predicted by size class, sex, and study period (pre/postdevelopment) and tagging location was input as a random effect. The best combination of these predictor variables was chosen through model AICc and parsimony, and predictors maintained in the best-fit model were assessed as influential. For these comparative models, data from sawfish tagged postdevelopment in Hooley Lagoon were excluded because no sawfish were tagged in this location predevelopment.

Overall space use of sawfish was examined using the actel v1.2.0 (Flávio & Baktoft, 2021) and RSP packages (1.0.0.9003) (Niella et al., 2020) in R. To do this, acoustic detections were imported into R and the shortest (in water) paths of each sawfish were calculated for all tracks throughout each deployment with a time delay of 30 days and a location error of 250 m. Subsequently, the use of these path spaces along with all detections received for each sawfish was input into a dynamic Brownian bridge movement model to estimate the utilization distributions for each animal throughout its deployment, essentially providing heat maps of estimated space use for each individual.

To determine the tendency of sawfish to swim past the PLF and MOF development area pre- and postdevelopment, the number of transits of this area for each month of each transmitter deployment was quantified. A transit was identified from the detection of a sawfish on one side of the development area followed by a detection on the opposite side, and the time of the transit was estimated at the time of the first opposite-side detection. To standardize comparisons of the number of transits from pre- and postdevelopment, only receivers present in both phases of the project were used to determine transits in statistical analyses. Because the number of transits per month per individual was highly zero inflated, a 2-part zero-inflated model with a Poisson distribution was used to describe transits, where the first part of the model assessed the probability of a transit occurring for a given individual and month and the second part of the model analyzed patterns in the number of transits for individuals in months where transits occurred. A series of zero-inflated Poisson distribution models were built with the pscl package 1.5.5 (Jackman et al., 2015) in R that included number of transits per month predicted by sex, TL (corrected for growth during deployment using estimated growth rates derived from Lear et al. [2023]), study period, tagging location, mean monthly water temperature, and total monthly discharge from the Ashburton River (determined from Western Australia Department of Water and Environmental Regulation river monitoring stations; https://kumina.water.wa.gov.au/waterinformation/wir/reports/publish/706003/706003.htm). A set of models with all possible combinations of these predictor variables was created, and the best-fit model was selected using AICc and parsimony. Confidence intervals for parameters maintained in the best-fit model were calculated using bootstrapping in the boot package 1.3-28 (Canty & Ripley, 2017) in R.

TABLE 1 Tracking data for green sawfish (*Pristis zijsron*) before and after development, including the total length (TL), transmission period, and residency of individuals in the receiver array.

Study period	*n*	Mean (SD) TL (mm), range	Mean (SD) transmission period (days), range	Mean (SD) residency in array (%), range
Predevelopment	37	1527 (663), 767–2933	172 (153), 6–524	62 (28), 10–100
Postdevelopment	60	1242 (621), 751–3195	254 (267), 4–635	80 (27), 5–100
Overall	97	1352 (650), 751–3195	221 (232), 4–635	73 (28), 5–100

Note: Data for all individual deployments are in Appendix S1.

RESULTS

A total of 39 individual green sawfish were captured in 2011, and 72 were captured between 2019 and 2022. No individuals were captured in both phases of the study. Of the captured sawfish, 37 were acoustically tracked between 2011 and 2013, and 60 were acoustically tracked between 2019 and 2022. Sawfish captured and tagged during both periods were of a similar size range (767–3195 mm TL) (Table 1). Metadata for all individual sawfish caught are in Appendix S1.

Tagged sawfish transmitted a total of nearly 290,000 detections in the predevelopment period and more than 1.1 million detections in the postdevelopment period. More receivers were deployed and a greater number of sawfish were tagged in the postdevelopment period. Transmission periods for externally tagged individuals during the predevelopment study phase ranged from 7 to 525 days (mean [SD] = 221 days [232]), and transmission periods for internally tagged individuals during the postdevelopment phase ranged from 4 to 653 days (mean = 253 days [267]) (Table 1). The longer deployments observed postdevelopment were most likely tied to the longer battery life of the latter generation of transmitters (652 vs. 514 days tag battery life), although differences in tag retention between externally and internally tagged fish may also have contributed. Water temperatures recorded from acoustic transmitters were similar in both phases of the study (range 10.3–35.5°C, mean = ~25.2°C). Sawfish depth use recorded by the acoustic transmitters was also similar between the 2 study phases: however, many depth transmissions in both phases recorded negative depths. Due to error in depth sensor accuracy in shallow depths (1.7 m), as communicated by the transmitter manufacturer, these negative depth readings likely represent shallow depths within the accuracy range of the sensor. However, some transmitters also read a constant negative depth throughout the full deployment. Although it is still possible that these readings represented consistent shallow depth use throughout the deployment, it is difficult to separate this possibility from a faulty depth sensor. Therefore, all negative depth readings were removed from the data for analyses of depth use. Without these readings, occupied depths of sawfish ranged from 0 to 11.96 m. Depth use generally increased as the size class of sawfish increased. Small YOY individuals were unlikely to occupy depths >2 m, and maximum and average depth increased as sawfish grew (Figure 2). There were no differences in the depth use of sawfish between pre- and postdevelopment phases.

Catch per unit effort

Across all sites, a total of 392 × 20-m net hours were fished in the predevelopment study period and 476 × 20-m net hours were fished in the postdevelopment period. The CPUE ranged from 0 to 0.53 sawfish per 20-m net per hour over separate locations and trips. Overall CPUE was 0.16 sawfish per 20-m net per hour over all sites and sampling periods. YOY CPUE ranged from 0 to 0.53 sawfish per 20-m net per hour across sampling locations and periods (or 0.067 YOY sawfish per 20-m net per hour overall). Age 1+ CPUE ranged from 0 to 0.36 sawfish per 20-m net per hour (0.079 age 1+ sawfish per 20-m net per hour overall).

No variables were influential in predicting overall CPUE, YOY CPUE, or age 1+ CPUE. The null model outperformed all other models in all cases (see Appendix S2 for model selection criteria). This indicates that CPUE (regardless of age class of sawfish) was not significantly affected by development and did not change significantly across sites within the study area or time of year.

Residency and space use

Individual residency within the entire array ranged from 5% to 100% and was slightly higher in the postdevelopment period (mean [SD] = 80% [27]) compared with the predevelopment period (mean [SD] = 62% [28]).

The best-fit model for predicting sawfish residency to their respective tagging locations maintained TL, study period (pre- or postdevelopment), and an interaction between TL and study period in the final model (see Appendix S2 for model selection criteria), indicating that these factors influenced residency of sawfish. Sex was not maintained as a fixed predictor, and the inclusion of tagging location as a random effect also reduced model fit (ΔAICc > 10), and was thus also not included in the final model. Residency of sawfish to their respective tagging locations generally decreased as TL increased in both periods of the study, but this trend was much more pronounced postdevelopment, with small sawfish showing much higher residency to their tagging location and large sawfish showing lower residency compared with tracking data from the predevelopment period (Figure 3). Because the receiver coverage within each tagging location was similar pre- and postdevelopment, these trends are unlikely to be an artifact of changes in the receiver array.

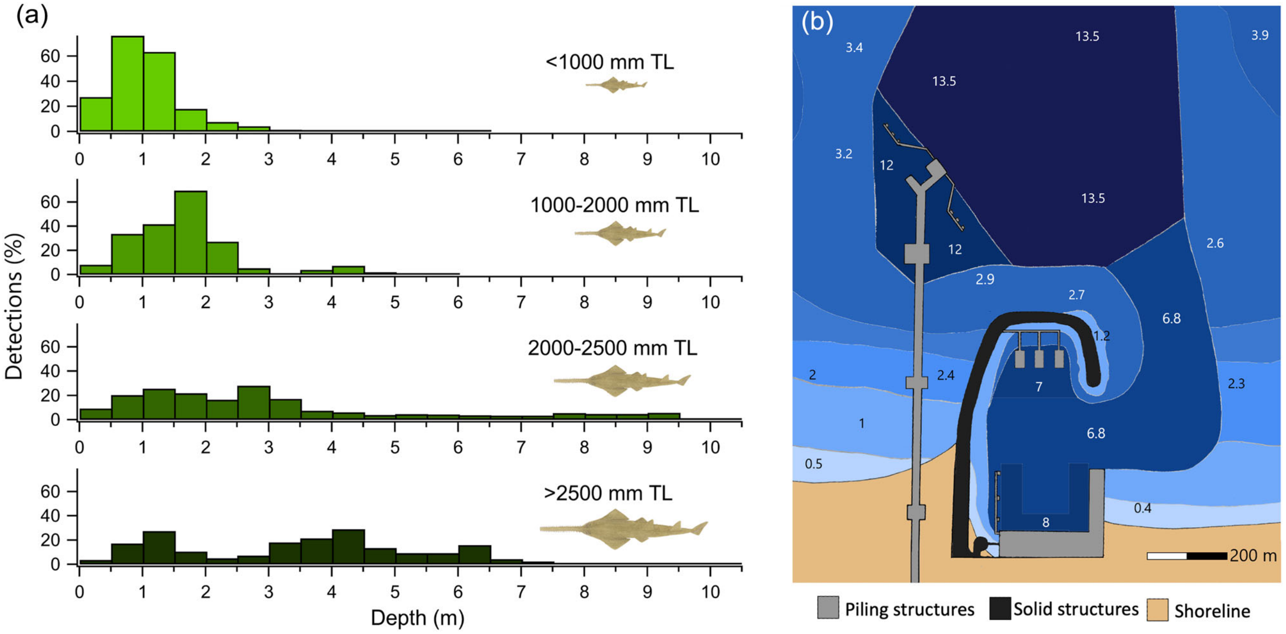

FIGURE 2 (a) Depths used by sawfish according to size class (i.e., percentage of depth transmitter detections per 0.5 m of water depth) (many negative depth detections were received during the study but were discarded due to uncertainty in the functionality of the depth sensor) and (b) approximate depth contours (at lowest tide) around the gas plant development area (the darker the shade, the deeper the depths; numbers show depth readings where available [adopted from Navionics Boating, Garmin Australasia, Marsden Park, New South Wales, Australia]; depths 6.8 - 13.5 m were dredged as part of the development; other depths show natural depth).

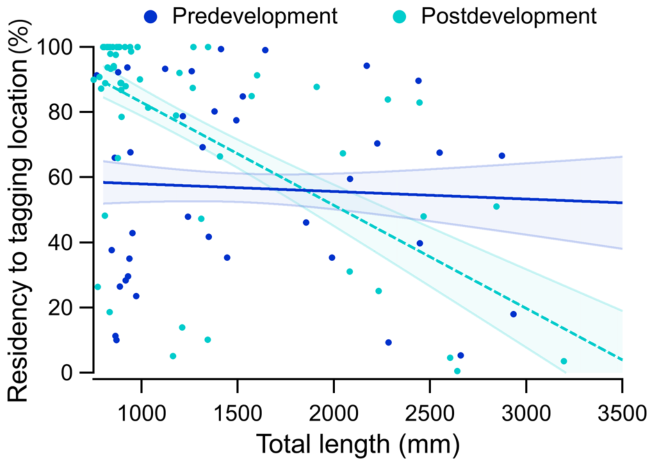

FIGURE 3 Trends in residency to tagging locations (percent of days detected at tagging location during tag deployment) for sawfish tagged in the Ashburton River, Hooley Creek, and Four Mile Creek before (dark blue, solid line) and after (teal, dashed line) development of the coastal infrastructure (points, residency indices for individual sawfish deployments; trend lines, predicted output of the best-fit linear model describing residency to tagging location; shading, 95% confidence intervals of the predictions).

Space use (as 25–50% utilization distributions) showed similar trends to residency; amount of area used increased as size increased. In both phases of the study, YOY sawfish tended to show utilization distributions limited to their tagging location, whereas older juveniles showed use of multiple nearby creeks. Predevelopment, sawfish of approximately >2000 mm TL began to show use of the full receiver array, whereas postdevelopment this pattern was not observed until juveniles reached approximately 2500 mm TL (Figure 4). The increased number of receivers present in the postdevelopment study phase allowed for a broader-scale examination of space use, particularly in larger sawfish. For example, acoustic transmissions confirmed multiple transits between the Ashburton River area and Urala Creek to the south of the study area (>25 km of coastline) for 2 individuals, which would have been an estimated 2800 and >3000 mm at the time of transit. The new receivers surrounding the development area also showed extensive use of the area directly to the west of the development by sawfish of all size classes but very little use of the area to the east of the development (except inside creek mouths for sawfish tagged at those locations) (Figure 4).

Transits across the development area

The best-fit model describing the probability of a sawfish transiting across the development area included sex, TL, and study period as informative predictors; water temperature, Ashburton River freshwater discharge, and tagging location were not maintained and thus were deemed not influential (see Appendix S2 for model selection criteria). These models indicated that in both study phases, female sawfish were more likely to transit the area than males and sawfish were more likely to transit the development area as they grew. Sawfish <2000 mm TL were not likely to make long-range transits through the area in either phase of the study; rather, these smaller sawfish tended to show high site fidelity to their tagging locations. Predevelopment

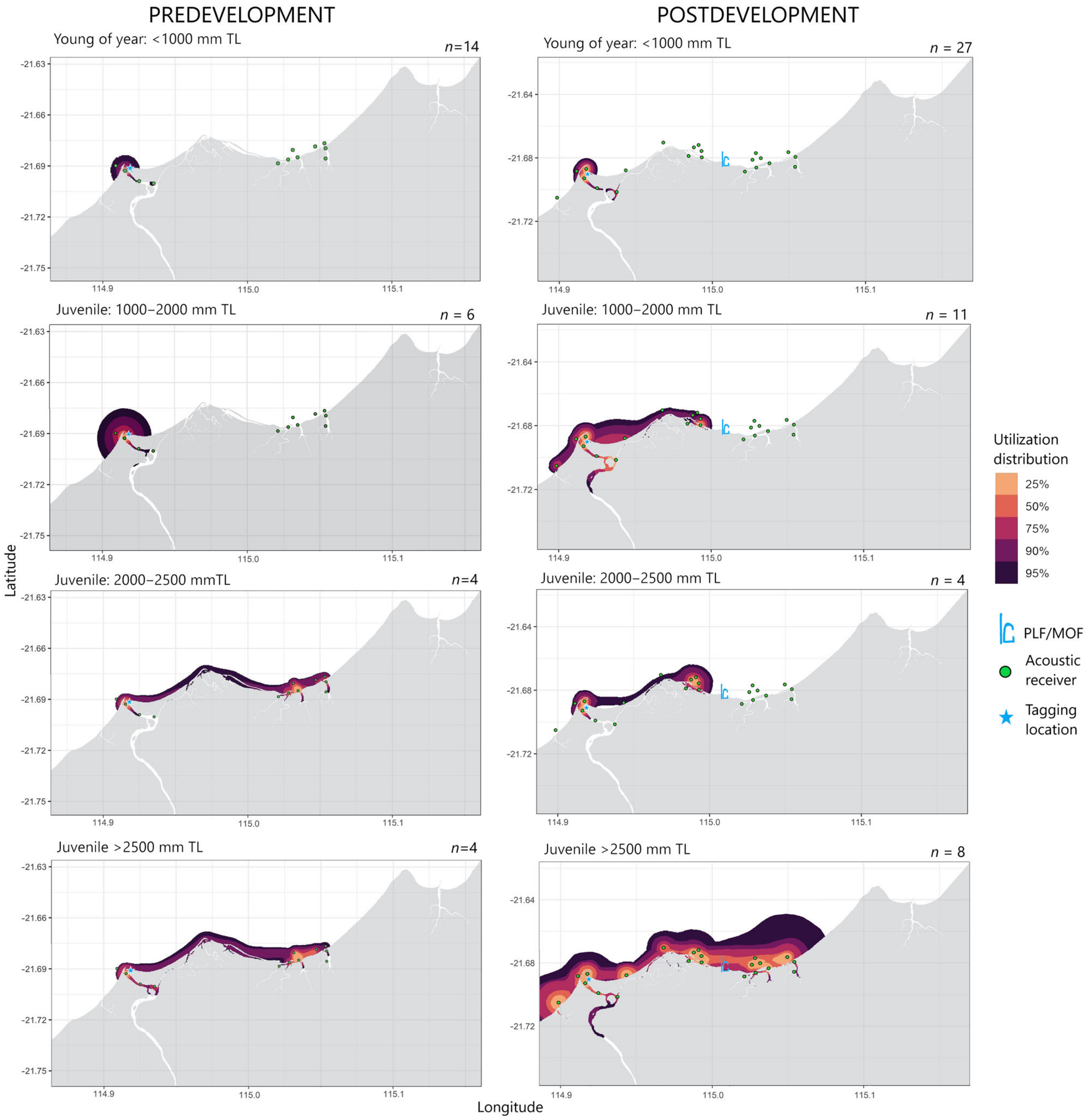

FIGURE 4 Utilization distributions (calculated via dynamic Brownian bridge movement models) for all sawfish of specific size classes tagged in the Ashburton River (blue star) before and after development of coastal infrastructure (green circles, positions of acoustic receivers; blue, location of the Product Loading Facility and Material Offloading Facility in postdevelopment panels). Only periods of the tag deployments where individuals were estimated to be within the specified size range were included in distribution modeling. Use areas show probability distributions of the location of a sawfish at a given time, so an individual of a particular size has a 25% probability of being within the orange boundary at any time, a 50% chance of being within the red boundary at any time, and so forth. There were several more receivers in the postdevelopment period than in the predevelopment period. Data from all receivers are shown here to present the most accurate available space use, but in some cases (e.g., juveniles 1000–2000 mm total length), the seemingly larger utilization distributions postdevelopment compared with predevelopment are likely an artifact of differences in receiver coverage.

sawfish began making longer transits and crossing the development area at approximately 2000 mm TL, but postdevelopment they were unlikely to make these transits until they reached more than 2500 mm TL (Figure 5). Additionally, modeling indicated that in larger juveniles making transits, sawfish of a given size were more likely to transit the development area before development than after development (Figure 5).

All of these modeling results describing tendency of sawfish to transit the development area were built only with data from acoustic receivers present in both phases of the study for

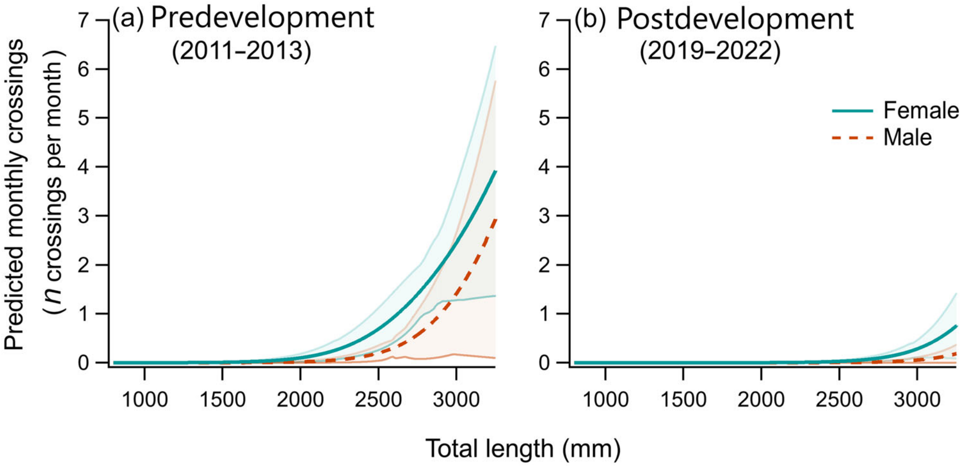

FIGURE 5 Probability of green sawfish (*Pristis zijsron*) transiting through the area (a) before and (b) after development of the coastal infrastructure in relation to total length and sex, as indicated by the best-fit zero-inflated model (shading, 95% confidence intervals of the model output).

comparability. As a result, a detected transit in these models (pre- and postdevelopment) required sawfish to travel over at least 13 km of coastline. It is likely that in the predevelopment phase of the study, many more (and smaller) sawfish transited back and forth across the development area but did not make a full 13-km transit. In the postdevelopment phase of the study, however, several additional receivers were placed closer to the newly constructed PLF and MOF, requiring a sawfish to travel only ∼2 km to be detected on receivers on one side of the development to the other. Even when considering detections from these nearby receivers postdevelopment, nearly all sawfish to transit around the PLF and MOF were individuals >2500 mm TL. The exception was 2 YOY sawfish that showed some evidence of crossings, described as follows.

The first small individual to cross the development was a sawfish of 871 mm TL (i.e., a neonate), which was detected for only 4 days in its tagging location (Hooley Lagoon; directly west of the development), transited across the development in 2.5 h, and was detected for approximately 8 h on offshore receivers (at ∼4 m depth) to the east of the development area before permanently leaving the array. The fast transit time across the development area (most other sawfish recording transits, even between nearby receivers postdevelopment, took more than 8 h to move across the development area), the uncharacteristically long time spent offshore in deeper waters (e.g., similar-sized sawfish are rarely found in waters deeper than 2 m), and the subsequent disappearance of this individual suggest that the tracked sawfish may have been predated, and these detections instead represented movements of a larger (likely carcharhinid) predator.

The second small individual to cross the development was also a neonate tagged in Hooley Lagoon, which remained within the array for 320 days and made 4 transits across the development area. These transits tended to take approximately 5–18 h, similar to the transit times recorded by larger sawfish. However, the depth readings from this individual's transmitter recorded regular excursions to >2-m depth, and up to 6-m depth, which is highly irregular for a sawfish of this size when compared with the depth profiles of other small sawfish in the study. In fact, this individual was the only sawfish <1000 mm TL out of 52 neonates tagged to provide any depth readings >3.5 m. These characteristics could also suggest that the tagged sawfish had been predated and that the transmitter was recording movements of a predator, although even large sharks tend to expel foreign bodies from their stomachs within days to months and it is perhaps more likely that this individual was just displaying unusual behavior for its size class. Either way, all the detections from both of these sawfish were recorded only on receivers that were not present in the predevelopment phase of the study; thus, they were excluded from statistical comparisons of transits. Even if the transits detected from the 2 YOY sawfish were accurately recorded, it is clear that sawfish using the area postdevelopment were less likely to move between creek systems compared with the predevelopment period.

DISCUSSION

This study represents a rare opportunity to empirically examine the effects of a coastal development on movement behavior of a mobile shoreline-associated species, where robust before and after data have been amassed (Underwood, 1997) and real-time behavior and habitat use response has been documented via telemetry of sawfishes. Although some differences in study design between the pre- and postdevelopment stages exist (e.g., higher sample sizes and number of receivers postdevelopment due to increased funding), we endeavored to standardize comparisons wherever possible, and these standardized results still indicated substantial changes in sawfish movement ecology from before to after development. Although complete preservation of natural ecosystems is ideal from a conservation perspective, there is a certain amount of inevitability of further development, particularly along coastlines, given a plethora of mounting anthropogenic pressures and uncoordinated activities (Waltham & Sheaves, 2015). Our results provide a strong indication that it is both crucial and urgent to accelerate understanding of design and engineering solutions to nearshore coastal infrastructure installations to limit long-term adverse effects on marine fauna, particularly with threatened species that rely exclusively on nearshore habitats to complete their life cycle. This is especially pertinent when accounting for cumulative impacts of multiple nearshore developments and effects of rising sea levels associated with climate change, which are likely to increase the extent of coastal hardening on a global level (Foti et al., 2020; Griggs & Reguero, 2021).

Responses to development

Our results showed that pupping of green sawfish is continuing in the Ashburton River delta despite current levels of development. This is a highly encouraging result, considering the importance of this region to the global conservation of green sawfish. However, a comparison of tracking data from before to after development does suggest that the construction of the piling jetty and rock wall has constrained juvenile sawfish movement throughout their nursery by acting as a barrier between different nursery creek systems.

The most likely explanation for the lack of sawfish movement past the new development (depending on size class) relates to the use of specific depths by sawfish as they grow. Ontogenetic depth partitioning (e.g., Knip et al., 2011; Whitty et al., 2009) and obligate use of shallow nursery habitats during juvenile stages (Heupel et al., 2007; Leurs et al., 2023) are common behavioral trends in elasmobranchs, most likely as strategies for small individuals to avoid predation risks inherent of deeper water. In this case, acoustic depth transmissions showed that most juvenile green sawfish <2500 mm TL were almost never detected in water more than 7-m deep, which is the approxmate minimum depth required for transit around the solid rock wall structure given the dredged entrance channel to the MOF. Excluding this dredged channel, sawfish would still be required to transit depths of ˜3-5 m (depending on tide) to circumvent the structure (see Figure 2), and even detections >3 m deep were rare. The development therefore acts as a barrier to the typical shoreline transit of these species by eliminating access to the shallow intertidal and immediate subtidal habitats that juvenile sawfish prefer. Furthermore, dredged channels for deepwater access of ships, often paired with nearshore developments, present large predators the opportunity to access shallow nearshore areas (Bradley et al., 2023; Leurs et al., 2023), potentially increasing predation pressure on nearshore fauna and exacerbating the consequences of movement around nearshore structures (e.g., Figure 6). Recent work has highlighted the importance of the shallow intertidal and direct subtidal habitats for a range of small-bodied and young elasmobranchs (Leurs et al., 2023), suggesting that the depth-related movement barriers shown here for sawfish are also likely to apply to a wider suite of taxa.

The rock-wall-induced movement constraints apparent in this sawfish nursery lend the question as to what effects such a barrier may have on the sawfish population or on similar species in the long term. The most obvious consequence of constrained movements is a potential decrease in home range size for small to midsize juveniles, as was observed with our tracking data. It is widely accepted that activity spaces of animals increase as they grow, which is attributed to the need for greater energy intake and therefore foraging opportunities in larger animals (e.g., Haskell et al., 2002; Lindstedt et al., 1986; McNab, 1963; Nash et al., 2015). For sawfish and other shallow-associated species, these expansions in activity space are typified by extending the length of the space used along the coastline, rather than extending their range into deeper water (see Figure 4). The development examined here prevents sawfish from extending their near-shore home range past the installed structures, potentially limiting foraging opportunities. Additionally, such a barrier can cause crowding to either side of the barrier, decreasing relative resource availability, potentially influencing growth and survival, and attracting predators. Such effects have been observed at freshwater and terrestrial barriers (e.g., Benstead et al., 1999; Middleton et al., 2020) and are likely to occur in the marine environment as well.

Because green sawfish reach large sizes as subadult and adult animals (adults up to at least 6000 mm TL), at which point they use depth contours that allow them to circumvent the rock wall development, the nursery barrier is unlikely to cause long-term population fragmentation. However, smaller-bodied species, including several shark and ray species that inhabit the study area, may never grow to a size where use of deep areas is common. In these species, barriers such as harbor walls or groynes may cause long-term fragmentation, genetic differentiation, or a loss of genetic diversity in some populations, as has been observed in terrestrial and freshwater taxa surrounding roads or dams (Holderegger & Di Giulio, 2010; Wofford et al., 2005).

Marine movement barriers and solutions

The potential of rock walls and other similar structures to impose major movement constraints to shoreline-associated species necessitates consideration of how to ameliorate some of these effects in both existing and future developments. Although there is negligible published information on this concept in coastal marine contexts, one can borrow from fauna passage experiences in terrestrial and riverine landscapes to envision scope for modeling or simulating passage scenarios, adaptive management in the field, controlled experiments, and sophisticated management approaches (Brennan et al., 2022; de Medeiros et al., 2022; Holdo et al., 2011; O'Connor et al., 2022; Zielinski et al., 2020). The robust science of barrier passage in freshwater and terrestrial landscapes amassed over the last several decades will be essential in promoting the rapid development of a similar breadth in marine barrier science.

Given the ubiquitous coastline developments already in place and an ever-mounting pressure for further coastal developments globally, a mature science and best-practice code of development is urgently needed within the scope of marine barriers. Of particular concern are the potential effects of

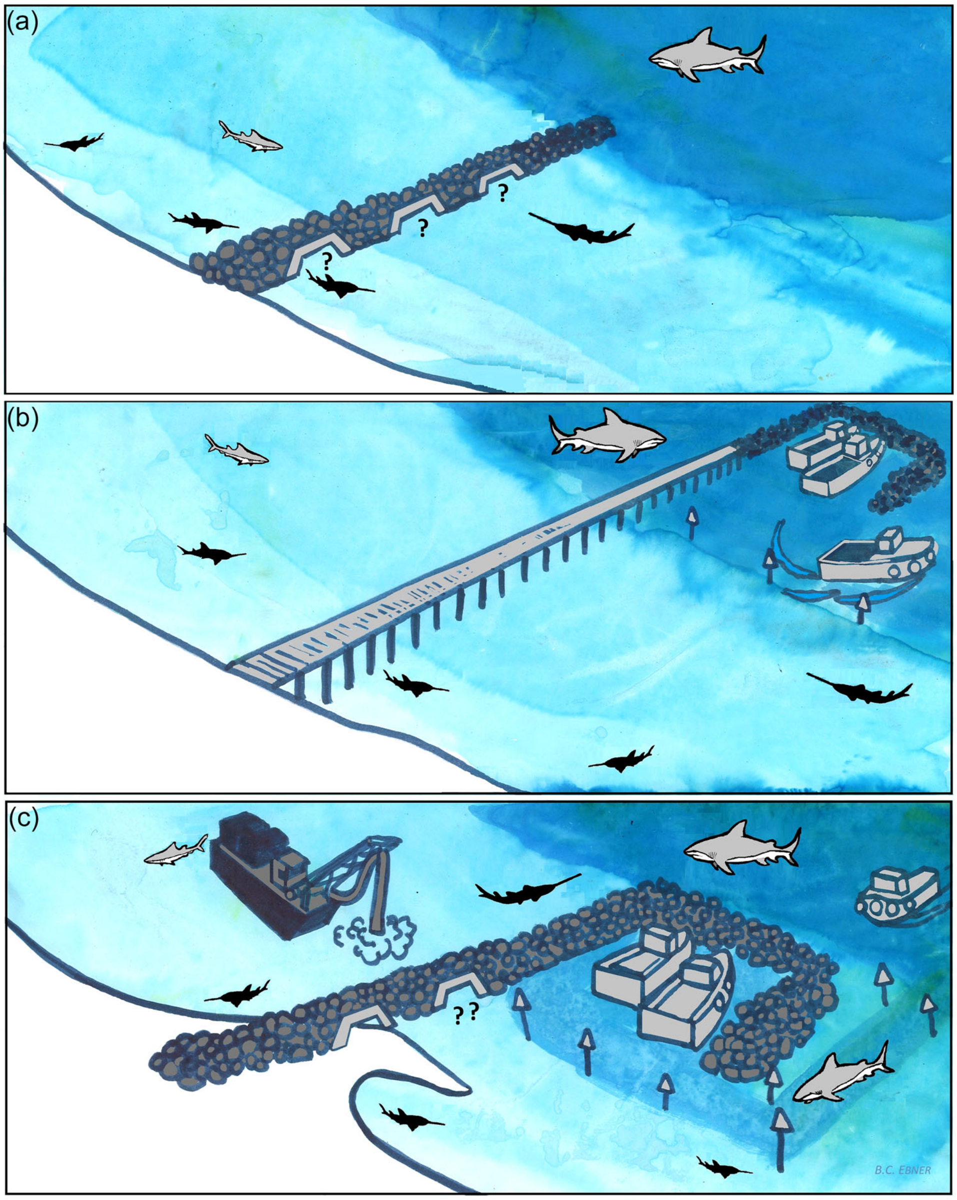

FIGURE 6 Potential solutions to the disruption of nearshore movement and predator–prey interactions by coastal infrastructure: (a) untested (denoted by '?') underpasses in simple rock wall scenarios, such as beach groynes; (b) harbors built offshore, connected by passable jetties, to minimize nearshore habitat disturbance; and (c) substantial nearshore habitat modification, including dredging ship access channels, maintaining the depth of an inshore harbor, and maintaining underpass access, noting that in this scenario large predator access to nearshore habitat is enhanced.

cumulative and often uncoordinated adjacent developments constructed without consideration of the movement patterns of shallow-water or shoreline-associated species. For example, there is currently a barrier similar to the one studied here approximately 15 km to the northeast of the study area, and several independent large-scale developments are proposed for this region in the near future, with facilities similar to the ones we examined (e.g., EPA, 2023a, 2023b; K+S Salt Australia, 2023). A sequence of shoreline barriers within migratory pathways is likely to greatly reduce and fragment the activity spaces of nearshore elasmobranchs and other shoreline-associated fauna; however, the environmental impacts of such developments are most often examined on a single development basis rather than cumulatively (Waltham & Sheaves, 2015). The interaction between segments of developments also has the potential to negatively affect fauna. For example, the rock wall we examined would likely not have had as pronounced an effect on sawfish movement if it had not been paired with dredged shipping channels, necessitating movement through even deeper areas to circumvent the development. Additionally, light and noise pollution from developments are likely to affect behavior and success of species (Chahouri et al., 2022; Davies et al., 2014), including movement ecology, but these effects are not well understood for most marine species. However, separate components within developments are often evaluated independently rather than concurrently; therefore, the cumulative effects of multiple development components are often missed. There is therefore an urgent need to investigate solutions to marine barriers that meld environmental and faunal benefits with sound structural engineering purposes and to coordinate consideration and strategic placement of structures (e.g., Munsch et al., 2017; Waltham & Sheaves, 2015).

There are also several potential structure-specific modifications that could enhance marine faunal passage through coastal developments (Figure 6). For example, incorporating single or multiple underpasses through solid structures, replacement of solid structures with permeable groynes (e.g., Bishop et al., 2017), or preserving shoreline habitat and migration routes by building structures strictly below the low tide line, perhaps connected to the shore through piling jetties or other passable structures (e.g., Munsch et al., 2017), would all enhance faunal movement around developments (Figure 6). All these potential solutions need robust experimentation to ensure their effectiveness for faunal passage (e.g., determining appropriate number and width of faunal passages [Brennan et al., 2022; Karlson et al., 2017]) and their suitability for structural engineering and compliance purposes. Additionally, the possibility of such structural modifications introducing new threats to fauna must be considered. For example, building jetties over shoreline habitat could increase recreational fishing access, and constricting faunal passage to specific points, such as underpasses, could increase predation risk if predators learn to take advantage of changes in prey movement behavior (e.g., sea lions and fish ladders [Keefer et al., 2012]).

Future considerations

Overall, we found that rock walls and deep trenches posed a challenge to juvenile green sawfish moving through a developed nearshore environment. Such structures would likely pose a similar challenge for other shallow water shoreline-associated fauna. We highlight the absence of instructive adaptive management experiences and a mature science on marine passage for mobile aquatic animals and suggest adaptive management centered on crossing solutions and comprehensive mapping of threatening processes and their synergistic interactions as immediate next steps. The intention is to open a dialogue that focuses on providing solutions for developers and environmental management agencies. Most importantly, the urgency for progressing a coordinated and considered plan that leads to data-driven decision-making is essential. Therefore, considerable investment in accelerated learning is required to produce solutions to marine barriers that will help conserve green sawfish along the northwestern Australian coastline, as well as nearshore marine ecosystems on a global scale.

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SUPPORTING INFORMATION

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