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RESEARCH PAPER
https://doi.org/10.1071/MF25015

MARINE & FRESHWATER RESEARCH

At-vessel mortality of tawny nurse sharks (*Nebrius ferrugineus*) caught in the Queensland Shark Control Program

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Handling Editor:
Bradley Wetherbee

Received: 22 January 2025
Accepted: 14 June 2025
Published: 10 July 2025

Cite this: Campbell MJ *et al.* (2025) At-vessel mortality of tawny nurse sharks (*Nebrius ferrugineus*) caught in the Queensland Shark Control Program. *Marine and Freshwater Research* **76**, MF25015. doi:10.1071/MF25015

ABSTRACT

Context. The Queensland Shark Control Program (QSCP) targets potentially dangerous sharks, using a combination of large-mesh nets and baited drumlines at beaches in Queensland, Australia. The tawny nurse shark (*Nebrius ferrugineus*) is caught incidentally by the QSCP, and shark control programs have been identified as a moderate threat to the species in Australia. **Aims.** Assessing at-vessel mortality (AVM) is an important first step in determining the actual impact of the QSCP on the *N. ferrugineus* population. **Methods.** Data collected by QSCP contractors were used to determine factors affecting AVM of *N. ferrugineus* and data were analysed using generalised linear mixed modelling. **Key results.** Mean AVM was 5.95 and 30.1% for those animals caught on drumlines and in nets respectively. At-vessel mortality was found to increase with total length for net-caught *N. ferrugineus*. Sea-surface temperature and sex had no effect on AVM. **Conclusions.** Animals caught on drumlines are more likely to survive capture than are those caught in nets. **Implications.** The reduction in the number of nets deployed, and the introduction of alternative methods, such as catch alert (or SMART) drumlines and drone surveillance of beaches, is likely to have reduced the impact of the QSCP on the *N. ferrugineus* population.

Keywords: at-vessel mortality, AVM, baited drumlines, chondrichthyans, Great Barrier Reef Marine Park, *Nebrius ferrugineus*, QSCP, Queensland Shark Control Program, respiratory mode, shark nets.

Introduction

Chondrichthyans (sharks, rays and chimaeras) have been the subject of increasing research efforts since the 1980s (Shiffman *et al.* 2020), owing to a lack of data required to assess populations and inform management (Simpfendorfer *et al.* 2011). Of the 1043 chondrichthyans for which sufficient data are available to assess the risk of extinction, 391 (~37%) are categorised globally as critically endangered, endangered or vulnerable to extinction, primarily as a result of incidental capture in fisheries targeting other species (Dulvy *et al.* 2021). Further, a recent study indicated that overfishing has halved the populations of 1119 sharks and rays since 1970 (Dulvy *et al.* 2024). Life-history strategies including slow growth, delayed maturity, low fecundity and long life spans make many chondrichthyan species vulnerable to over-exploitation (Ellis *et al.* 2008) and inhibit recovery of depleted populations (Simpfendorfer *et al.* 2011).

One species that faces a high risk of extinction is the tawny nurse shark (Orectolobiformes; Ginglymostomidae, *Nebrius ferrugineus* Lesson, 1830), which is listed as 'vulnerable' according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Simpfendorfer *et al.* 2021). *Nebrius ferrugineus* occurs in tropical Indo-Pacific waters, from eastern Africa to Tahiti, where it is exploited for its meat, liver, oil, fins and hide (Last and Stevens 2009). This, combined with habitat loss throughout its range, has resulted in a 30–49% reduction in the global *N. ferrugineus* population (Simpfendorfer *et al.* 2021). However, Australia provides a refuge for *N. ferrugineus*, and other threatened, globally distributed coastal and shelf chondrichthyans (Kyne *et al.* 2021), primarily as a result of well-managed fisheries (Dulvy *et al.* 2024).

In Australia, *N. ferrugineus* is classified as 'least concern' across its distribution (Kyne *et al.* 2021). Although incidentally caught in two large penaeid-trawl fisheries, legislation requiring the use of turtle excluder devices (TEDs), introduced in the early 2000s, has reduced the capture of *N. ferrugineus* by 100% (Kyne *et al.* 2021). Apart from these fisheries, no *N. ferrugineus* have been landed by the Queensland commercial net fishery (source: https://qfish.fisheries.qld.gov.au/), whereas the recreational catch of *N. ferrugineus* is unknown (source: https://www.daf.qld.gov.au/business-priorities/fisheries/monitor/rec/statewide-survey#view-the-data), but is not likely to affect the Queensland population significantly (Kyne *et al.* 2021). As such, the only source of possibly significant fishing mortality affecting the *N. ferrugineus* population in Queensland waters is the Queensland Shark Control Program (QSCP). The QSCP is a bather protection program implemented in the early 1960s after several fatal shark bites (Sumpton *et al.* 2011). Potentially dangerous sharks, primarily tiger sharks (*Galeocerdo cuvier* Péron & Lesueur, 1822), bull sharks (*Carcharhinus leucas* Valenciennes), and white sharks (*Carcharodon carcharias* Linnaeus, 1758), are targeted using a combination of large-mesh nets and baited drumlines at beaches along the Queensland coastline (Sumpton *et al.* 2011). At the program's inception, 76 baited drumlines and 30 nets were deployed across 29 beaches in the following 5 broad regions: Cairns, Townsville, Mackay, the Sunshine Coast and the Gold Coast. In 2024, 383 drumlines and 27 nets were deployed across the state (Fig. 1).

Because of the concerns relating to interactions with non-target animals, the use of nets by the QSCP within the boundaries of the World Heritage-listed Great Barrier Reef Marine Park (GBRMP) was progressively reduced until 2017, when all nets had been replaced by baited drumlines. In 2020, the Great Barrier Reef Marine Park Authority, the regulatory body responsible for managing activities within the GBRMP,

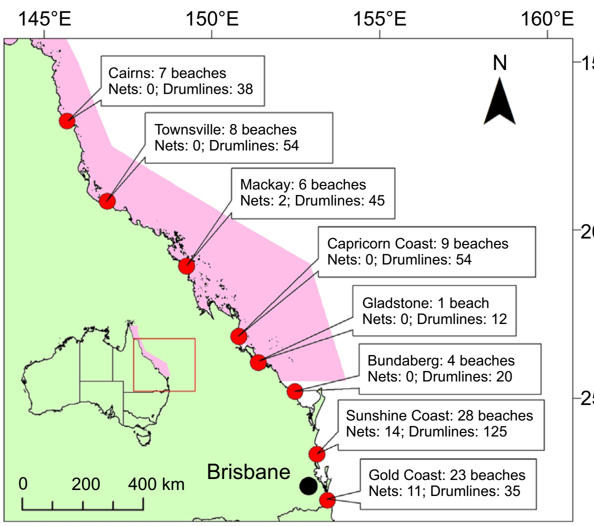

Fig. 1. Location of each Queensland Shark Control Program (QSCP) region, outlining the number of beaches within each region and the number of nets and drumlines deployed in 2024. The pink-shaded area represents the extent of the World Heritage-listed Great Barrier Reef Marine Park.

limited the use of baited drumlines, such that (1) the equipment is serviced every 24 h where possible, (2) all animals caught by drumlines are released alive when safe to do so, and (3) *G. cuvier*, *C. leucas* and *C. carcharias* are tagged and relocated offshore. These conditions have been implemented by the QSCP since 17 February 2020. Prior to this time, contractors were required to service QSCP equipment at least every 3 days, weather permitting, and any target species caught were euthanased. Servicing was also undertaken on weekends, during school holidays and on public holidays, when beach use was highest.

The impact of the QSCP on the *N. ferrugineus* population in Queensland is currently unknown. Kyne *et al.* (2021) identified shark control programs as a moderate threat to *N. ferrugineus* in Australia; however, all *N. ferrugineus* must be released alive if possible after capture by QSCP gear. As such, an important first step in assessing the threat posed to the Queensland population of *N. ferrugineus* by the QSCP is to quantify mortality resulting from interactions with QSCP gear. Post-release mortality (PRM) is the proportion of individuals that die during, or as a result of, catch and release and accounts for any immediate or delayed effects of physical or physiological trauma experienced by an individual (Ellis *et al.* 2017). Although quantifying PRM is ideal, the cost and logistical constraints of experimentally deriving PRM estimates, using cage or tank experiments or satellite tagging, can be prohibitive (Musyl and Gilman 2019).

Owing to these limitations, researchers assess at-vessel mortality (AVM), which is defined as the proportion of individuals that are dead when brought on-board (or alongside) a fishing vessel (Ellis *et al.* 2017). Quantifying AVM improves the accuracy of fishing mortality estimates used to assess chondrichthyan stocks (Dapp *et al.* 2016; Matias Braccini and Waltrick 2019), and can be used to inform the management and conservation of chondrichthyans (Sulikowski *et al.* 2020; Gilman *et al.* 2022). Previous studies have shown that AVM is species-specific (Rodríguez-Cabello and Sánchez 2017; Matias Braccini and Waltrick 2019; Mucientes *et al.* 2022) and is influenced by factors such as respiratory mode and gear type (Dapp *et al.* 2016), fish size (Carruthers *et al.* 2009), soak time (Lyons *et al.* 2013; Matias Braccini and Waltrick 2019; Gulak and Carlson 2021), hooking time (Morgan and Carlson 2010; Butcher *et al.* 2015) and water temperature (Massey *et al.* 2022).

The objective of the current study was to quantify the AVM of *N. ferrugineus* caught in nets and on drumlines deployed by the QSCP to help inform the ecological risk posed to the species by the program.

Materials and methods

Fishing equipment and servicing

Sumpton *et al.* (2011) provided a description of the gear used throughout the QSCP (see https://www.daf.qld.gov.au/news-media/campaigns/sharksmart/equipment for illustrations of the gear used). In summary, the nets used are constructed of 1.6 mm diameter polypropylene twine with a mesh size of 50 cm. The nets have a drop of 12 meshes and are between 124 and 186 m long, depending on location. Generally, drumlines consist of a single 14/0 J-shaped shark hook baited with a single fresh sea mullet (*Mugil cephalus* Linnaeus, 1758) or shark flesh (*Charcharhinus* spp.) suspended 2 m below a buoy and at least 2 m from the seafloor at low tide. Suspending baits above the seafloor reduces incidental captures of benthic non-target elasmobranch species, while not affecting catch rates of potentially dangerous sharks (Lipscombe *et al.* 2023). Drumlines are anchored to the substrate using a length of 12-mm polypropylene rope three to four times the depth of the water. Drumlines and nets are anchored to the seafloor ~600 m from, and parallel to, the shore, in water depths between 6 and 12 m.

From the beginning of the program, in 1962, until 17 February 2020, QSCP equipment was deployed year-round, and serviced every 1–3 days, depending on weather. Servicing was undertaken during the day, mostly during the morning, and the time taken to service the gear was dependent on the number of nets or drumlines deployed. At the start of each service day, contractors recorded abiotic data such as sea-surface temperature (SST, °C). During the service, any live target sharks were euthanised and discarded ~1 km seaward of the capture location, whereas any live, non-target species, including *N. ferrugineus*, were released at the capture location as soon as practicable. Contractors recorded relevant data such as species, size (m, total length, TL, for sharks and Rhinopristiformes, disc width for remaining batoids), sex and alive or dead (AVM). Animals were considered dead if no body, eye or gill movement was detected or if rigor mortis was obvious. During each service, drumlines were rebaited. When required, drumlines and nets were recovered for cleaning and maintenance, and immediately replaced. During periods of forecast severe weather (e.g. cyclone), some equipment was temporarily removed from the water.

In the period between 18 February 2020 and 30 April 2024, service frequency of drumlines located within the GBRMP increased to daily, with a minimum of 21 services undertaken per month. Baits are removed and hooks are attached to the buoy to render them ineffective when not in use such as during significant weather events that would prevent scheduled servicing. No nets were in use within the bounds of the GBRMP during this period. All animals were released alive where possible, and any *G. cuvier*, *C. leucas* and *C. carcharias* inividuals were tagged with external acoustic tags or dart tags before being released approximately 1 km seaward of the capture location. Outside of the GBRMP, servicing continued as per the period prior to 17 February 2020; however, the contractors operating in the Cairns and Mackay regions serviced the gear inside the GBRMP 260 days year^{-1} and 182 days year^{-1} outside the GBRMP (Fig. 1), whereas contractors operating in the Capricorn Coast and Townsville regions serviced all equipment 260 days year^{-1}.

The trial was conducted under Marine Park Permit number G17/33288.1 and Queensland Department of Agriculture and Fisheries Animal Ethics approval CA 2021/03/1482.

Statistical analysis

Data were obtained from the QSCP catch database. All catch records between 1 January 1995 and 30 April 2024 were examined and the dataset was restricted to those cases where a *N. ferrugineus* was caught, and data on size, sex, SST, and AVM were recorded. A trial of catch alert drumlines (CADs, aka SMART drumlines) commenced in the Capricorn Coast region in 2021, before the trial was extended to the Cairns and Mackay regions in February 2024. Catch alert drumlines are similar to the drumlines used throughout the QSCP, but include a satellite communication unit that sends an alert to the contractor when an animal is hooked. This allows contractors to immediately attend to the hooked animal, facilitating its tagging, relocation and release. Any *N. ferrugineus* caught using CADs were excluded from the analyses to avoid bias when estimating AVM.

At-vessel mortality was assessed using generalised linear mixed models (GLMM). At-vessel mortality was the response variable, modelled as a binomial distribution where 0 = alive and 1 = dead. Beach was added as a random term, whereas gear type (net, drumline), month (January to December), and sex (male, female) were added as categorical factors to assess their effect on the probability of survival. A dummy binary variable (0 = before, 1 = after), representing the change to daily servicing within the GBRMP, was also added to determine the effect of this change. Further, size and SST were added as continuous covariates. Categorical terms and covariates were tested for significance and retained in the model only if a significant effect was detected and their addition reduced the Akaike information criteria (AIC). Relevant two-way interactions were also tested and excluded if their addition had no significant effect on AVM. The AVM was estimated using *R* statistical software (ver. 4.0.2, R Foundation for Statistical Computing, Vienna, Austria, see https://www.R-project.org/, accessed 6 November 2024) using the 'glmer' function within the *lme4* package (ver. 1.1-23, see https://CRAN.R-project.org/package=lme4; Bates *et al.* 2015). The 'bootMER' function within the *lme4* package was used to generate 95% confidence intervals around the estimated probabilities.

Results

In total, 772 *N. ferrugineus* individuals were caught by QSCP contractors in the period between 1 January 1995 and 30 April 2024. Sea-surface temperature was absent in 47 cases, one total length was not recorded, and sex was indeterminable for 17 animals. Consequently, AVM was estimated from the capture of 707 individuals (Supplementary Tables S1 and S2), 428 (60%) of which were female. The total length of females (mean = 2.38 m, s.d. = 0.37 m) and males (mean = 2.41 m, s.d. = 0.37 m) did not differ significantly ($t = -1.03$, d.f. = 631, $P = 0.30$). However, the 92 *N. ferrugineus* individuals caught in nets (mean = 2.51 m, s.d. = 0.35 m) were significantly larger ($t = 3.23$, d.f. = 121, $P < 0.01$) than the 615 individuals caught on drumlines (mean = 2.38 m, s.d. = 0.36 m) (Fig. 2).

Nebrius ferrugineus was more common in northern regions (Fig. 3, Tables S1, S2). In total, 306 *N. ferrugineus* sharks were caught in the Townsville region, only two of which were caught in nets (Table S1). Of the 141 *N. ferrugineus* individuals caught in the Cairns region, 30 (~21%) were caught in nets, as were 57 of the 179 idndividuals (32%) caught in the Mackay region. Only drumlines were deployed in the Capricorn Coast, Gladstone and Bundaberg regions during the study period.

Of the 92 *N. ferrugineus* individuals caught in nets, 32 (~35%) were dead when caught, compared with 42 of the 615 (~7%) caught on drumlines. The GLMM indicated that the increasing size of *N. ferrugineus* caught in nets resulted in higher AVM (net × TL: $\beta = 0.957$, s.e. = 0.367, $P = 0.009$). Sex ($P = 0.386$), SST ($P = 0.586$), month ($P = 0.199$) and the dummy variable representing the change to daily servicing within the GBRMP ($P = 0.644$) had no significant effect on survival. Similarly, the drumline × TL interaction term had no effect on AVM ($P = 0.556$). The AVM of *N. ferrugineus* caught on drumlines was 5.95% ($CI_{\alpha = 0.05}$ = 4.38–7.76%) and 30.1% ($CI_{\alpha = 0.05}$ = 20.18–41.84%) for those caught in nets at the mean TL of animals caught by the respective gear types (2.38 and 2.51 m respectively) (Fig. 4).

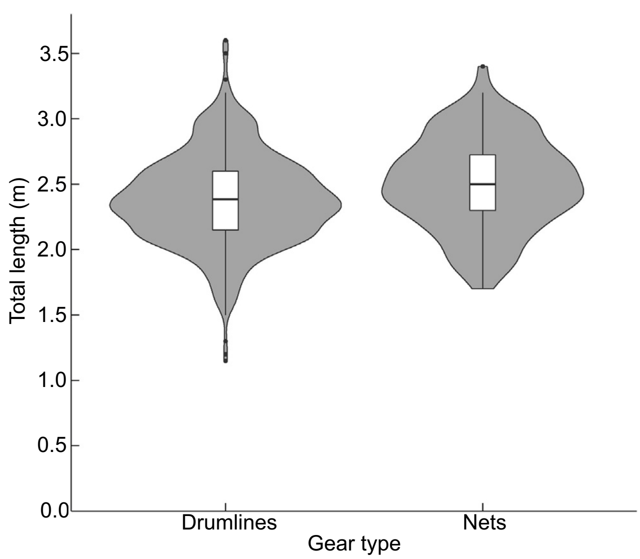

Fig. 2. Violin plot of length, as a function of gear type, for 707 tawny nurse sharks (*Nebrius ferrugineus*) caught by the QSCP between 1 January 1995 and 30 April 2024. Also shown is a box and whiskers plot for length as a function of gear type.

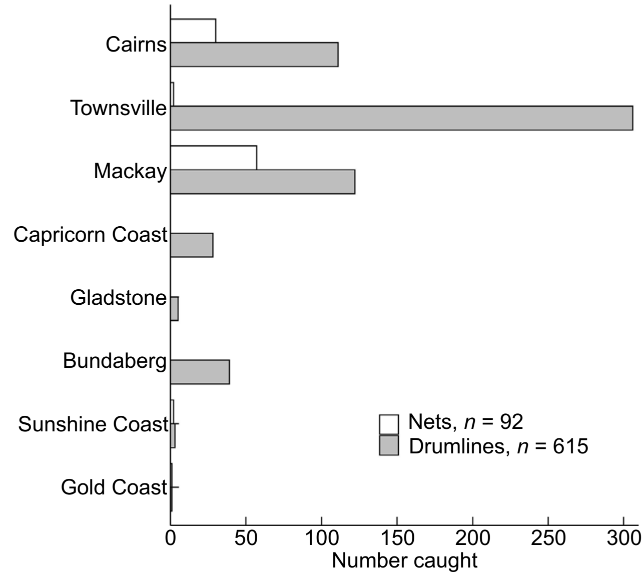

Fig. 3. Number of tawny nurse sharks (*Nebrius ferrugineus*) caught in each QSCP region between 1 January 1995 and 30 April 2024, sexes combined, as a function of gear type. Note: nets were not deployed at any beach within the Capricorn Coast, Gladstone and Bundaberg regions during the study period.

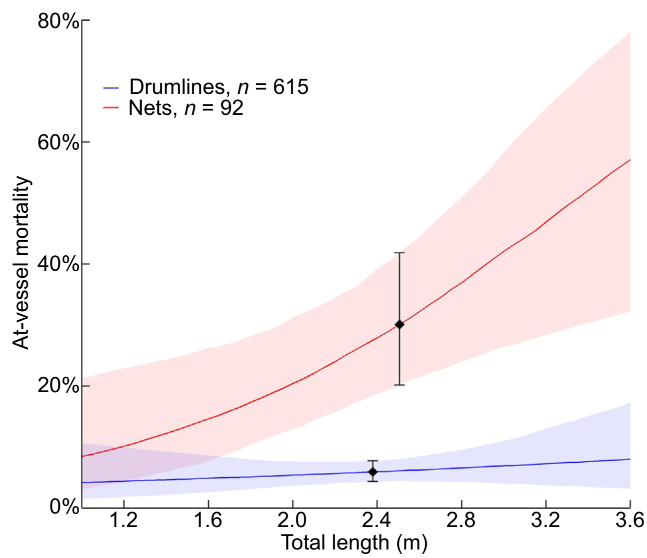

Fig. 4. At-vessel mortality (AVM) of tawny nurse sharks (*Nebrius ferrugineus*) caught in nets and on drumlines between 1 January 1995 and 30 April 2024, as a function of total length. The black points are the estimated AVM of *Nebrius ferrugineus* at the mean total length of the individuals caught on the respective gear types (drumlins = 2.38 m; nets = 2.51 m).

Discussion

These results represent the first AVM estimates for *N. ferrugineus* in the primary literature. Generally, *N. ferrugineus* was resilient to capture on baited drumlines deployed as part of the QSCP. However, AVM was higher for animals caught in nets, particularly for larger individuals. This result is consistent with that of Sumpton *et al.* (2011), who demonstrated that the AVM of chondrichthyans caught in the QSCP was highest when caught in nets. Similarly, Dapp *et al.* (2016) found that the AVM of elasmobranchs was higher when caught in gillnets, than when caught on longlines. The higher AVM for net-caught *N. ferrugineus* in the current study is likely to be related to heavy entanglement around the gill region, such as that reported for the gummy shark (*Mustelus antarcticus*) (Frick *et al.* 2010), which restricts water flow through the gills, even for species that can buccal pump to irrigate the gills. Further, the correlation between AVM and the total length of net-caught *N. ferrugineus* observed in the current study is consistent with the results of Braccini *et al.* (2012), who reported that larger chondrichthyans were less likely to survive capture in bottom-set gillnets in southern Australia, than are smaller conspecifics. Restricted water flow through the gills as a result of heavy entanglement, combined with the higher oxygen consumption (Sims 1996) and proportionally less oxygen uptake (Bouyoucos *et al.* 2019) in larger individuals, may explain this result.

In contrast, individuals caught on hooks are able to swim while tethered by the gear (Frick *et al.* 2010), allowing respiration while hooked. As a result, chondrichthyans caught using baited hooks tend to exhibit lower AVM than those caught in gillnets (Dapp *et al.* 2016; Ellis *et al.* 2017). After the initial acute stress response on hooking, the ability to swim facilitates some physiological recovery (Brooks *et al.* 2012), which may reduce AVM and PRM. In the current study, J-hooks were used throughout the QSCP; however, trials of circle hooks are underway to determine their effect on catch and AVM. Numerous studies have shown that circle hooks reduce AVM or PRM (e.g. Godin *et al.* 2012; Reinhardt *et al.* 2018; Gilman *et al.* 2022), primarily by reducing the incidence of deep hooking (Gilman *et al.* 2016). Further, circle hooks have been shown to reduce the capture (Yan *et al.* 2025) and deep hooking (Santos *et al.* 2024) of sea turtles, a group occasionally caught incidentally in the QSCP (Gribble *et al.* 1998; Sumpton *et al.* 2011). Replacing J-hooks with circle hooks in the QSCP will likely further reduce AVM for *N. ferrugineus*, and outputs from the trial of circle hooks currently underway will inform future management of the QSCP.

The low AVM of hook-caught *N. ferrugineus* is consistent with that reported for the confamilial Atlantic nurse shark (*Ginglymostoma cirratum* Bonnaterre). Whitney *et al.* (2021) and Morgan *et al.* (2009) reported 0% AVM for *G. cirratum* caught on bottom-set longlines used in separate US fisheries. Both *N. ferrugineus* and *G. cirratum* can respire while stationary, by buccal pumping, a method of respiration that contributes to lower AVM, than for obligate ram ventilators (Dapp *et al.* 2016). Clearly, constraining the movement of obligate ram ventilators will reduce the volume of water moving through the gills, whereas species capable of buccal pumping can continue to respire despite being hooked. For example, Whitney *et al.* (2021) reported that the AVM of blacktip, blacknose, and spinner sharks was 35, 35 and 62% respectively, all of which are obligate ram ventilators. Similarly, Sumpton *et al.* (2011) reported 66.3–80% AVM for obligate ram ventilating carcharhinids caught in QSCP nets, compared with 10.5–19.7% AVM for batoids, which respire while stationery, through spiracles.

Apart from the estimates published by Whitney *et al.* (2021) and Morgan *et al.* (2009) for *G. cirratum*, very little AVM information is available for any of the Orectolobiformes (Ellis *et al.* 2017). Sumpton *et al.* (2011) observed that 10 of the 49 zebra sharks (*Stegostoma tigrinum* Forster, 1781) caught in QSCP nets died during their study (AVM = 20.4%), whereas the only individual caught on a drumline survived. Both Walker *et al.* (2005) and Braccini *et al.* (2012) reported 0% AVM for gillnet-caught spotted wobbegongs (*Orectolobus maculatus*) caught in a southern Australian gillnet fishery, although sample size was low (n = 4 and 5 respectively). Additionally, Braccini *et al.* (2012) reported an AVM of 12.5% for the rusty carpetshark (*Parascyllium ferrugineum* McCulloch, 1911, n = 24) and 20% for the varied carpetshark (*Parascyllium variolatum* Duméril, 1853, n = 4). Matias Braccini and Waltrick (2019) assessed the AVM of chondrichthyans caught by demersal longlines in Western Australia and found that the AVM of *S. tigrinum* (n = 8), and wobbegongs (*Orectolobus ornatus* de Vis, 1883 and *Orectolobus* spp., n = 3) was 0%. The results of this study, as well as those from data-limited prior research, indicate that species of Orectolobiformes generally exhibit low AVM. However, further research is required to determine survival in the longer term, given the potential for delayed effects of physical trauma or physiological stress (Skomal 2007).

It should be noted that the soak times for the drumlines or nets deployed during the current study was higher than those in the studies conducted by Whitney *et al.* (2021), Morgan *et al.* (2009), Walker *et al.* (2005) and Braccini *et al.* (2012). Whereas soak times in the current study were 1–3 days, the maximum soak time among the compared studies was ~20 h in the Braccini *et al.* (2012) study. This author found that AVM and soak time were inversely correlated and, as a result, it is difficult to compare results from the current study with those from previous studies. Further work is required to determine the effect of implementing daily servicing within the GBRMP; however, reducing the soak time of QSCP gear is likely to result in lower AVM than that derived in the current study.

The nets used throughout the QSCP caught larger *N. ferrugineus* than did baited drumlines. This is consistent with previous studies of chondrichthyans caught by the QSCP (e.g. Simpfendorfer 1992; Holmes *et al.* 2012; Haig *et al.* 2018). For example, Haig *et al.* (2018) found that *C. leucas* individuals caught on drumlines were, on average, 0.4 m smaller than those caught in nets. Therefore, it is reasonable to assume that the removal of nets from the GBRMP is likely to have resulted in a decrease in mean length at capture over time for species such as *C. leucas*, *G. cuvier* and *N. ferrugineus*, particularly when comparing current sizes to those from periods when more nets were deployed (*c.* pre-1990). A decline in the size at capture of sharks over time has been linked to overfishing for species interacting with the QSCP (Haig *et al.* 2018) and other fisheries (e.g. Braccini 2017). However, ignoring the effect of gear type, and other operational factors such as hook size, bait type and trace length, on size and species composition of individuals caught in the QSCP over a long period can lead to spurious conclusions and ill-informed recommendations.

The community has expressed concerns about the impact of the QSCP on marine fauna, particularly non-target animals such as whales, dolphins and dugongs, in QSCP nets (Gribble *et al.* 1998). Similarly, recent research inferring the QSCP may be responsible for declining shark populations (Roff *et al.* 2018), or declines in the functional diversity of sharks (Henderson *et al.* 2024), has been cited as evidence for the removal of nets and drumlines in Queensland. The QSCP is trialling alternatives to nets and traditional drumlines to address community concerns. Trials are currently underway to determine the efficacy of CADs (Campbell and Scott-Holland 2023) and circle hooks on the catch and survival of target and non-target animals. Further, unmanned aerial vehicles (UAVs or drones) are being trialled as a method of identifying potentially dangerous sharks (Mitchell *et al.* 2022), enabling lifeguards to evacuate beaches to reduce risk to swimmers.

The implementation of these measures is likely to reduce the impact of the QSCP on the Queensland population of *N. ferrugineus*. The current study has shown that the AVM of *N. ferrugineus* caught on drumlines is low, and preliminary data indicate that AVM is 0% when caught on CADs (M. Campbell, unpubl. data). As such, the QSCP is likely to pose low ecological risk to the Queensland *N. ferrugineus* population. However, an understanding of the actual ecological impact of the QSCP requires further research into PRM and population dynamics. Future studies should focus on (1) quantifying long-term catch and release using survivorship pop-up archival transmitting (sPAT) tags or acoustic telemetry utilising Queensland's expanding acoustic array (Barnett *et al.* 2024), and (2) an ecological risk assessment to determine the effect of current levels of fishing mortality on the long-term sustainability of the *N. ferrugineus* population in Queensland.

Supplementary material

Supplementary material is available online.

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Authorship contribution. Matthew Campbell provided the conceptualisation, formal analysis, investigation, methodology, validation, visualisation, writing of the original draft, and review and editing. Tracey Scott-Holland contributed data curation, investigation, writing of the original draft, and review and editing. Samuel Fary undertook investigation, writing of the original draft, and review and editing. Matthew McMillan contributed to the writing of the original draft, and review and editing.

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. All authors were funded by the Queensland Department of Primary Industries for this research.

Acknowledgements. The authors thank the QSCP contractors for their continued diligence in reporting catch and survival data. Glynis Fowler collated and managed the QSCP data, and we thank her for help throughout this study. Michael Mikitis and Natale Snape provided helpful comments on an earlier draft of this paper. Special thanks go to Helen McPherson for her assistance in sourcing and supplying relevant literature.

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