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Trends in catch rates of sawfish on the Australian North West Shelf

Alastair V. Harry[1,2,*], Corey B. Wakefield[1], Stephen J. Newman[1], J. Matias Braccini[1]

[1]Western Australian Fisheries and Marine Research Laboratories, Aquatic Science and Assessment, Department of Primary Industries and Regional Development Western Australia, Hillarys, Western Australia 6025, Australia

[2]Centre for Sustainable Aquatic Ecosystems, Harry Butler Institute, Murdoch University, Murdoch, Western Australia 6150, Australia

ABSTRACT: Northwestern Australia is thought to have some of the world's last remaining viable sawfish populations, although little quantitative data exists on their status or trends. This study examined 17 years of logbook bycatch records (n = 815) for green sawfish *Pristis zijsron* and narrow sawfish *Anoxypristis cuspidata* from a trawl fishery operating on the Australian North West Shelf. Incidental sawfish captures by the fishery are rare, occurring approximately once every 75 trawls (~199 trawl hours). To standardize catch rates and account for excess zeros in the data, we employed generalized additive models for location, scale, and shape (GAMLSSs) using a zero-inflated Poisson distribution. For green sawfish, catch rates approximately doubled over the study period, while an oscillating trend was observed for narrow sawfish catch rates. Reported captures occurred throughout the management boundaries of the fishery, which operates in mid-shelf waters from 48 to 121 m. A weak seasonal signal in catch rates was detected for both species, with the highest capture numbers occurring during autumn—winter, consistent with an expected inshore migration for parturition during spring—summer. Logbook trends were partly corroborated by independently verified data collected in a subset of years, which also showed an increasing proportion of green sawfish in the catch. Our findings emphasize the importance of sawfish populations in northwestern Australia within the context of global conservation efforts for this taxon.

KEY WORDS: Pristidae · Trawling · Bycatch · Index of abundance

1. INTRODUCTION

Sawfish are one of the most imperiled groups of marine fishes, with all 5 extant species threatened with extinction and listed as Critically Endangered by the International Union for the Conservation of Nature (IUCN 2023). Overfishing has been the primary cause of population decline, coupled with habitat loss, in particular within the nearshore, estuarine, and freshwater ecosystems used by juveniles (Dulvy et al. 2016, Yan et al. 2021). In an attempt to conserve populations, sawfish have been added to a range of international conventions and treaties and are now protected in 16 of the 90 countries in which they have historically been reported (Dulvy et al. 2016). Australia and the USA have implemented sawfish recovery plans, and a global strategy for sawfish conservation was released by the IUCN Species Survival Commission in 2014 (Harrison & Dulvy 2014).

Measuring the success of conservation and management actions for sawfish is limited by a lack of data on population trends. Conspicuous features of sawfish, such as their large body size and toothed rostra, along with apparent high former abundance in many regions, have enabled historical population declines and range contractions to be inferred from numerous sources, including fisheries catch data (Thorson 1982, Simpfendorfer 2002), shark control programs (Everett et al. 2015, Wueringer 2017), interviews (Jabado et al. 2017, Braulik et al. 2020, Tanna et al. 2021), museum

*Corresponding author: alastair.harry@gmail.com

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records (Ferretti et al. 2016), historic newspapers and photographs (Hudgins et al. 2020), and preserved rostra (Leeney & Downing 2016, Fearing et al. 2018).

Understanding of contemporary population trends is limited. Aside from a small number of monitoring programs in juvenile nursery areas (Morgan et al. 2015, Lear et al. 2019), population trends are mostly inferred from fishery-dependent sources that are often highly uncertain (Carlson et al. 2007, Fry et al. 2018). Relatively few countries across the distributional range of sawfish require and enforce bycatch reporting in fisheries, and in those countries that do, the large size of sawfish and risks to human safety from handling entangled individuals make accurate data collection difficult. In fisheries that have human observers, a prohibitively high level of observer coverage may be needed to make robust inferences about bycatch of rare and threatened species (Kuhnert et al. 2011). For example, Wakefield et al. (2018) found that an observer coverage of ~70% would be needed to estimate levels of sawfish bycatch with a high degree of certainty.

The Pilbara Trawl Fishery (PTF), which targets demersal teleosts on the Australian North West Shelf, is a rare example of a fishery that has been able to address data collection issues and successfully implement sawfish bycatch monitoring. Understanding and mitigating the impact of demersal fish trawling on protected species and the wider ecosystem has been a longstanding priority for the diverse, multispecies fisheries operating across northern Australia (Sainsbury 1991, Sainsbury et al. 1993, Wassenberg et al. 2002). Concerns over bycatch, in particular mortality of bottlenose dolphins *Tursiops truncatus*, have led to an extensive body of research on bycatch composition and mitigation methods that includes fishery-independent surveys (CSIRO 2022), observer-based monitoring (Stephenson & Chidlow 2003), deck-mounted and subsurface video monitoring (Wakefield et al. 2014, Santana-Garcon et al. 2018), and gear modifications, including the implementation and assessment of various bycatch reduction devices (Stephenson & Wells 2008, Wakefield et al. 2017).

For the PTF, this work has culminated in the adoption of bycatch monitoring and reporting requirements to comply with Australian environmental legislation (EPBC Act 1999). Vessels operating in the PTF are required to keep detailed logbooks that have been validated using a combination of methods, including satellite vessel monitoring systems since 1998, human observers at a coverage of 8–17% per year from 2002 to 2009, and electronic monitoring at a coverage of 85 and 78% per year in 2012 and 2016, respectively. The present-day logbooks provide a spatially resolved record of catch and effort, including species-specific reporting of the 2 species of sawfish incidentally captured by the fishery: green sawfish *Pristis zijsron* and narrow sawfish *Anoxypristis cuspidata*.

This study examined catch rates of sawfish incidentally caught by the PTF using logbook records between 2006 and 2022. We used zero-inflated generalized additive models for location, scale, and shape (GAMLSSs) to examine the influence of temporal factors and depth on sawfish catch rates with the aim of developing standardized, catch-rate based indices of abundance for green and narrow sawfish. To corroborate trends in logbook catch rates, we also analysed temporal trends in sawfish catch composition from independent observer and electronic monitoring data using a generalized additive model (GAM). The results of this study provide information that directly informs the sustainable management of sawfishes in northwestern Australia and other locations where data and resources are limited.

2. MATERIALS AND METHODS

2.1. Data collection

Data on individual trawls and corresponding sawfish captures were obtained from statutory fishing logbooks used by the PTF. Logbooks are self-reported, physical documents filled out during each fishing trip, and their format remained consistent over the duration of the study. The spatio-temporal information recorded in logbooks included the start and end time, date, depth, and start and end location (latitude and longitude) of each trawl. Although logbooks are self-reported, a variety of mechanisms are in place to ensure compliance with reporting requirements. For example, a satellite vessel monitoring system (VMS) is mandatory and used to manage fishing effort (Joll et al. 1999). Licence holders are required to submit separate catch disposal records at the point of catch unload that are cross-referenced with logbook catch.

Data on protected species incidentally captured during fishing operations are required to be reported in logbooks for each trawl. For sawfishes, vessel masters are asked to record the species (N: narrow sawfish *Anoxypristis cuspidata*, G: green sawfish *Pristis zijsron*), fate (D: dead, A: alive), and number captured. The start of this study corresponds to the implementation of a bycatch action plan for the fishery which included the mandatory introduction of bycatch reduction devices and increased verification of logbook records. Over the duration of the study, between 2 and 6 stern trawlers operated annually in the fishery. The trawl gear configuration used by PTF vessels did not undergo major changes during this period, and thus sawfish catchability was assumed to be similar.

2.2. Data analysis

2.2.1. Catch rate

Sawfish captures are rare, occurring in fewer than 2% of all trawls (Fig. S1 in the Supplement at www.int-res.com/articles/suppl/n053p023_supp.pdf) and resulting in a highly imbalanced response variable (count of sawfish per trawl). Additionally, most sawfish catches involved only a single individual (96 and 95% of positive events for green and narrow sawfish, respectively, Fig. S1). To examine temporal patterns in the number of sawfish captures and allow for nonlinear relationships between predictors and the response variable, we used GAMLSSs with a zero-inflated Poisson distribution. The choice of a Poisson distribution was based on preliminary analyses that showed sawfish count data were not overdispersed, suggesting a negative binomial distribution was not required. Additionally, due to the low contrast in the number of positive cases (typically 1 sawfish caught per positive case), the Poisson component of the GAMLSS (mean catch given sawfish presence), was modeled as an intercept only.

Categorical explanatory variables included in the presence component of the model were calendar year, required for building an annual index of abundance, and vessel. Although 9 vessels operated in the PTF during the study period, the catch rate analysis was restricted to 3 that fished consistently over the duration of the study. The remaining 6 vessels fished intermittently and in fewer than 5 calendar years. Cumulatively, these 6 vessels made a relatively small contribution to the total catch (see results), and they were removed from the analysis for quality control purposes, since their participation in the fishery and logbook records were intermittent.

Month and depth were continuous explanatory variables in the model and fitted as smoothing terms: month as a cyclic cubic regression spline, and depth as a thin plate regression spline. Depth was calculated as the mean of the start and end depths of trawling. To calculate sawfish density and account for fishing effort, ln(swept area) was included as an offset term in the presence component of the model. The approximate swept area (km^2) of each trawl was calculated as:

$$\text{swept area} = \frac{\text{distance} \times \text{headrope} \times \text{wing spread}}{1\,000\,000}$$

where the trawl distance in meters was calculated from the start and end point of fishing, and the trawl headrope length used was in meters. In the absence of data on trawl wingspread, a value of 0.5 was chosen (Sparre & Venema 1998).

Missing values of predictor variables in the analysis were handled with multiple imputation using bagged regression trees (Murray 2018, Kuhn 2022). For depth, missing values (0.18% of records) were imputed from latitude and longitude, while missing values of trawl distance (0.42% of records) were imputed from trawl duration, total catch, discards, and depth. Sawfish logbook records were typically identified to species level, although in some cases only a number was provided (i.e. species was missing). On trips with fisheries observers or electronic monitoring, unknown records were assigned to species level based on the data collected. Likewise, if an error in logbook records was found (e.g. green sawfish recorded in logbook, observer identified narrow sawfish), the logbook record was also corrected. The remaining missing values of species (6.13%) were imputed using a simple random sampling approach for each year (Gelman and Hill 2006).

GAMLSS regression models for green and narrow sawfish were implemented in R using the 'mgcv' package, and parameters were estimated using restricted maximum likelihood (Wood 2011). The 'predict' function included in the R base package was used to obtain marginal effects for year, month, vessel, and depth (R Core Team 2022). We set continuous terms to their means, and categorical terms to their most common value (Maunder & Punt 2004). Confidence intervals were calculated using asymptotic errors.

2.2.2. Logbook verification

Previous independent verification of logbook records using electronic monitoring in 2016 found that 94% of sawfish captures were recorded (C. B. Wakefield unpubl. data), suggesting logbooks accurately reflect bycatch numbers; however, accuracy of logbooks with respect to species identification is less clear. To better understand the validity of species-specific trends in logbook reporting, we examined temporal trends in independently verified sawfish records collected by fisheries observers or through electronic monitoring. For this analysis, sawfish species was treated as a binomial response variable in a GAM (narrow sawfish = 0, green sawfish = 1), and date of capture was treated as a continuous variable (decimal date). Change in green sawfish capture probability as a function of time was modeled using a thin plate regression spline. Analysis of deviance was used to test whether there was a significant change in sawfish catch composition through time. Data from all vessels were included in this component of the analysis. ANOVA was also used to compare the mean length of sawfish recorded by observers during this period.

3. RESULTS

Between 2006 and 2022, there were 815 sawfish reported in the PTF logbooks, comprising 479 green sawfish, 286 narrow sawfish, and 50 individuals not identified to species (Fig. 1). There was a decreasing trend in overall fishing effort between 2006 and 2015, followed by an approximately 50% increase since 2016. Total effort comprised 61 344 trawls and 161 794 trawl hours, corresponding to 1 sawfish being captured approximately every 75 trawls or 199 trawl hours. Total sawfish catch and nominal catch rates were stable or slightly increasing over the study period.

Narrow sawfish were common in the logbook records at the start of the time series before declining (Fig. 1, Fig. S2). In comparison, the total catch of green sawfish and their proportion in the catch increased over the time series, particularly from 2016 onward. On average 94 ± 7.1% (mean ± SD) of logbook records were reported to species level annually. Reported sawfish captures were distributed throughout the boundaries of the fishery (Fig. 2). The shallowest and deepest records were 48 and 121 m for green sawfish and 50 and 117 m for narrow sawfish, which represents the approximate depth range the PFT operates in.

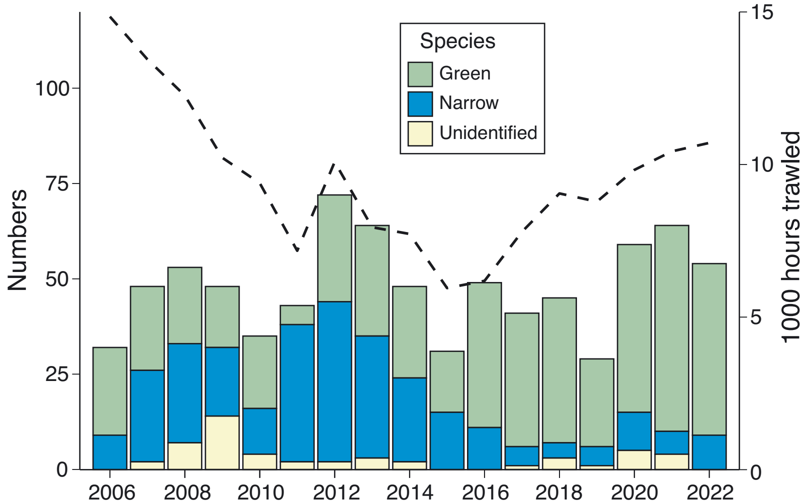

Fig. 1. Reported sawfish catch in fisheries logbooks and corresponding fishing effort (dashed line) between 2006 and 2022

3.1. Catch rates

Data from 3 vessels that operated continuously during the analysed time period, which were used in the catch rate analysis, comprised 83% of logbook records (n = 50 785 trawls) and included 720 total sawfish captures. Of these, 47 records were not identified to species level and were imputed from the reported logbook proportions in their year of occurrence. Independent verification of logbook data was possible for 107 green and 42 narrow sawfish (i.e. 22% of all records) using data collected by electronic monitoring or fisheries observers.

In the GAMLSS regression models for both species, all included variables were statistically significant predictors of sawfish presence (Table 1); however, the overall deviance explained by the model was low (<10%) due to the highly zero-inflated nature of the catch. The effects of the included model terms on sawfish presence are shown in Fig. 3. For green sawfish, there was a steady increase in swept area catch rates over the time series, which approximately doubled from 0.71 sawfish per 100 km^2 in the first 5 yr to 1.49 per 100 km^2 in the last 5 yr. Narrow sawfish catch rates oscillated, increasing from 0.17 per 100 km^2 in 2006 to 2.74 per 100 km^2 in 2011, before declining to 0.44 per 100 km^2 in the last 5 yr.

There was a weak seasonal signal in the catch rates of both species, with the highest catch rates in July and the lowest in late October. For green sawfish, an increase in mean catch rate was most apparent over the austral autumn–winter (April to August), while for narrow sawfish, catch rates were higher between February and August. The effect of depth, while statistically significant, was highly uncertain, particularly around the maximum and minimum depths. For green sawfish, catch rates increased steadily to around 50 m depth before plateauing, and no clear

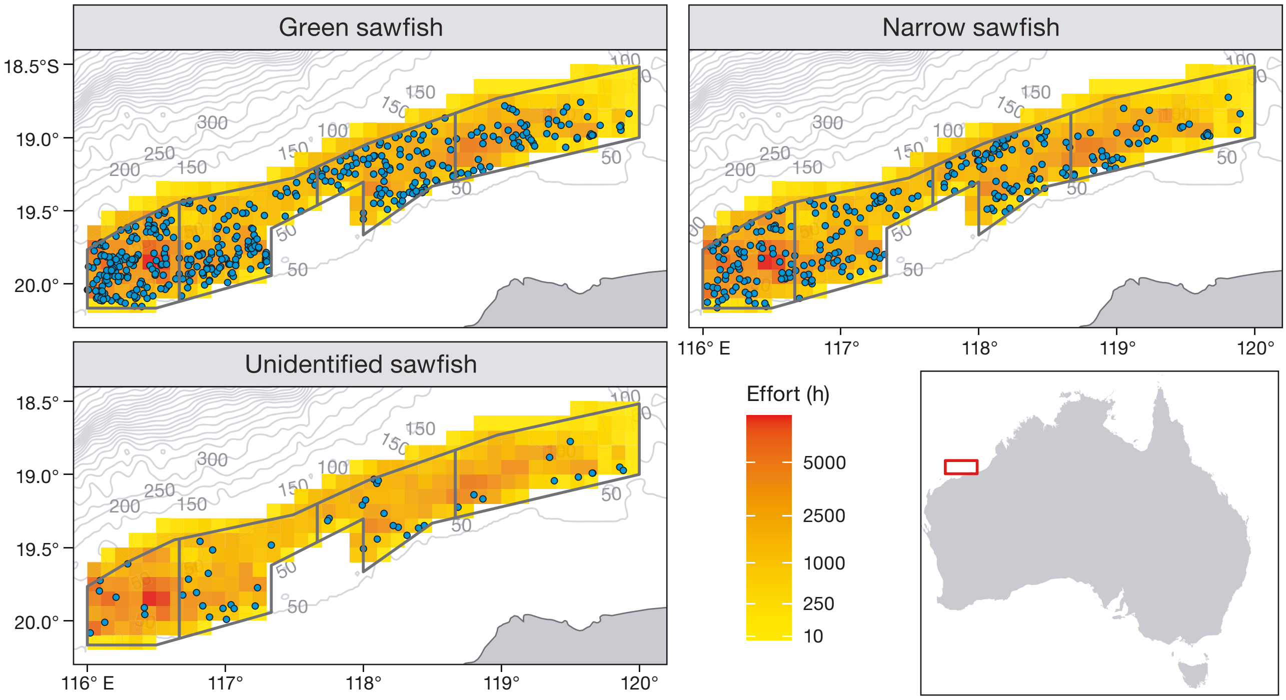

Fig. 2. Spatial distribution of fishing effort (trawl hours) and reported sawfish captures (blue circles) in the Pilbara Trawl Fishery between 2006 and 2022

Table 1. Analysis of deviance table for the GAMLSS zero-inflated Poisson models showing the statistical significance of terms for predicting sawfish presence. Note mean sawfish catch given presence was modelled as an intercept only

Species	Term	P (>Chi)	p
Green sawfish	Year	74.21	<0.01
	Vessel	57.43	<0.01
	Month	88.09	<0.01
	Depth	14.92	0.011
Deviance explained		7.58%	
Narrow sawfish	Year	97.43	<0.01
	Vessel	69.77	<0.01
	Month	58.69	<0.01
	Depth	15.41	<0.01
Deviance explained		9.00%	

trend was evident for narrow sawfish. Statistically significant differences in catch rates of both species were also evident between vessels, with catch rates for one vessel markedly lower than the others.

3.2. Logbook verification

A total of 187 sawfish were recorded by fisheries observers or electronic monitoring across all vessels in the fleet between 2002 and 2020, comprising 130 green and 57 narrow sawfish. A GAM fit to the sawfish catch composition data indicated a statistically significant change in species composition of sawfish over the time period (analysis of deviance: $\chi^2 = 16.98$, df = 3.98, $p < 0.01$) (Fig. 4). A simple logistic regression was also parsimonious given the data (analysis of deviance: $\chi^2 = 11.19$, df = 1, $p < 0.01$). Both models suggested an increase in the proportion of green sawfish in the catch over time.

While the overall trend in independently verified data was consistent with logbook data, there was still a clear discrepancy between the 2 sources in several years, with fewer green sawfish reported in the logbooks than would be expected (Fig. 4). For example, 40% of logbook records (n = 68) in 2012 were reportedly green sawfish. This compares to a value of 60% based on independently verified records (n = 37) from electronic monitoring (Fig. 4).

During observer surveys between 2002 and 2010, fishery observers measured or estimated lengths for 41 sawfish. Statistically significant differences in size were evident between the 2 species (Fig. 5, ANOVA: $F = 47.02$, df = 1, 39, $p < 0.01$). The length of green sawfish (n = 25) was 408 ± 67 cm (mean ± SD), while the length of narrow sawfish (n = 16) was 272 ± 54 cm. This indicates the catch of both species is likely primarily composed of adult fish (Peverell 2005, Lear et al. 2023).

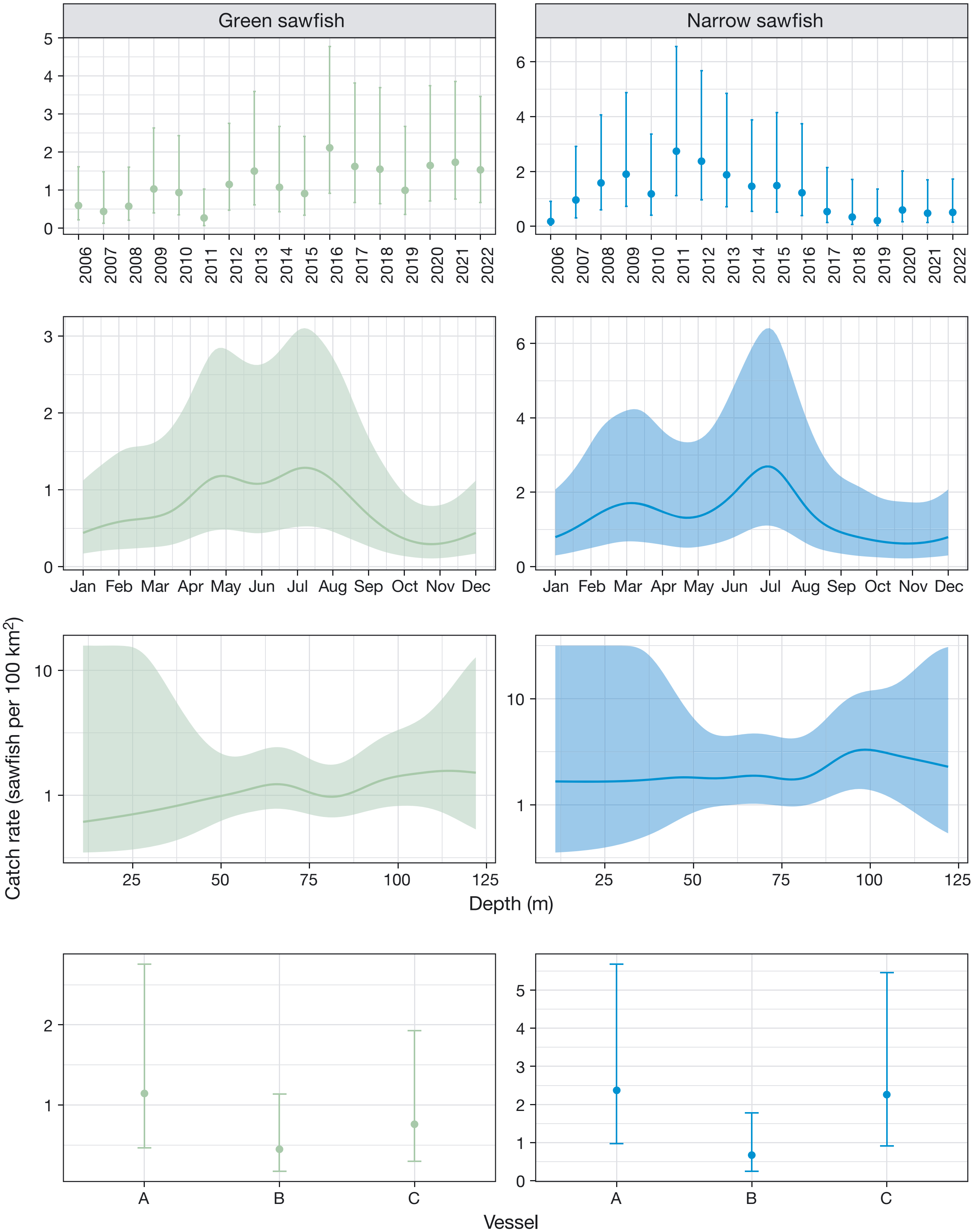

Fig. 3. Predicted effects (±95% CI) of year, month, depth, and vessel on catch of green and narrow sawfish. Note that the *y*-axis for depth has been square root transformed to display uncertainty

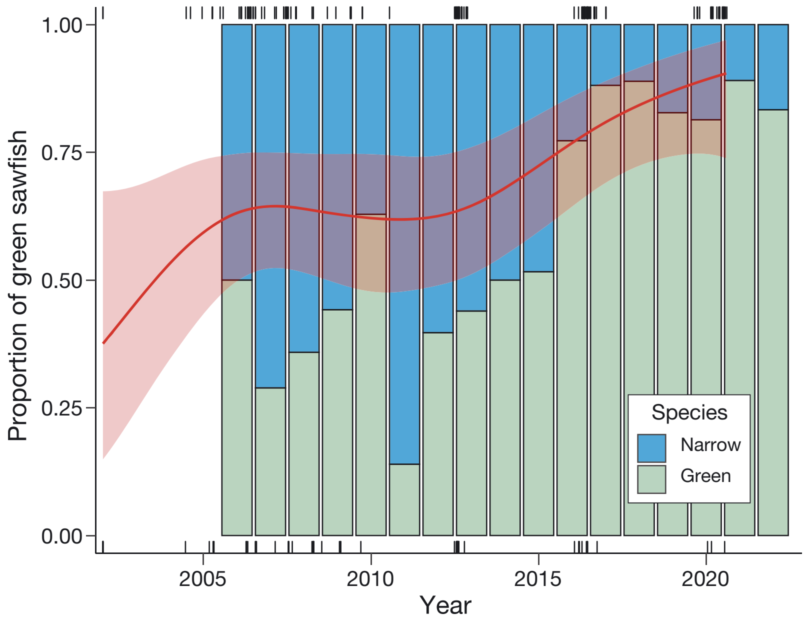

Fig. 4. Proportions of green and narrow sawfish bycatch in the Pilbara Trawl Fishery over time. The red solid line and shaded area are the estimated proportion of green sawfish in the catch (±95% CI) based on independently verified data. Rug plots in the margins show raw data points (upper = green sawfish, lower = narrow sawfish). Shaded bars are the proportion of the 2 species reported in fisheries logbooks

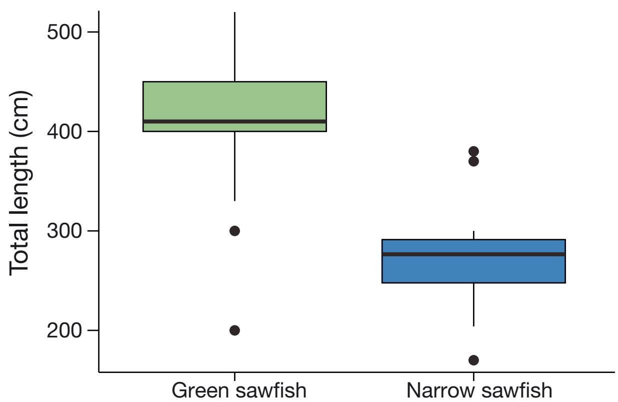

Fig. 5. Boxplot of green (n = 25) and narrow (n = 16) sawfish total lengths collected by fisheries observers between 2002 and 2010

4. DISCUSSION

We analysed bycatch records from 17 years of fisheries logbooks to develop indices of relative abundance for green and narrow sawfish on the Australian North West Shelf. Standardized catch rates of green sawfish increased over the study period, while those of narrow sawfish showed an overall flat, albeit fluctuating, trend. Catch rates of both species were influenced by depth, fishing vessel, and month, showing evidence of a seasonal trend. Our findings suggest a potential increase in the abundance of green sawfish in recent years. This conclusion is supported by an increasing trend in annual catch, along with an increasing proportion of green sawfish in independently verified records from observer and electronic monitoring. However, observer data also suggest some of the increase may have been attributed to reporting practices. The results of this study are the first species-specific population trend data for either species at the regional or global scale, underscoring the paucity of data available for sawfish. In addition to informing conservation and management of these species within Australia, they provide insights into aspects of sawfish ecology and the nature of their interactions with fisheries that are of wider relevance.

4.1. Sawfish trends on the North West Shelf

The results of this study suggest flat or increasing trends in the abundance of sawfish populations on the North West Shelf. But is such an assessment realistic given the poor status of most populations globally, including in other parts of Australia? To answer this, it is worth considering the current and historical level of commercial fishing within the region. The 17 yr time series of this study corresponds with a period of relatively low fishing intensity within the PTF and more broadly across the North West Shelf. From 1959 to 1989, the North West Shelf was fished intensively by distant-water trawl fisheries, leading to changes to benthic habitats and fish communities (Sainsbury et al. 1993, Moran 2000, Wassenberg et al. 2002). Since the prohibition of foreign fleet fisheries, limited-entry Australian fisheries have operated at a lower intensity, shifting towards other methods that don't capture sawfish (i.e. trap and line fishing). In recent decades, the implementation of management measures to increase target species biomass coupled with ongoing fleet rationalization has resulted in decreased trawl effort, with typically only 2 vessels operating full time. Present-day fish trawling has been constrained under legislation to an area of

23 215 km^2 since 1998, constituting around 11% of the total North West Shelf (Joll et al. 1999, Lebrec et al. 2022). The actual footprint of the area trawled each year is likely to be smaller than this (see Amoroso et al. 2018).

Over the last 2 decades, there has also been a reduction in the intensity of inshore fisheries, including the closure of nearshore gillnet fisheries that operated within putative sawfish nursery areas (Pember 2006). While poorly documented, these fisheries were characterized by a large bycatch of both narrow and green sawfish in areas such as Eighty Mile Beach, which was closed to commercial fishing in 2008 (McAuley et al. 2005, Fletcher & Santoro 2009). There has also been a reduction in penaeid trawling in the region, and the closure of the WA North Coast Shark Fishery in 2005, both of which had some level of incidental sawfish catch (Salini et al. 2007). In 2005, sawfish were protected under state legislation, preventing their retention in all commercial and recreational fisheries.

One hypothesis is that reduced fishing intensity, coupled with the relatively intact coastal habitats along the North West Shelf, may have enabled sawfish populations to recover following a presumed historical decline, and this is reflected in the increasing green sawfish catch rates. In Florida (USA), for example, a prohibition on gillnetting in inshore waters led to an increase in smalltooth sawfish *Pristis pectinata* abundance (Carlson et al. 2007, 2022). This hypothesis is also consistent with the high abundance of juvenile green sawfish observed in nursery areas in the Pilbara region in recent years (Morgan et al. 2015, 2017), and is realistic in the context of generation lengths for the 2 species, which is 5 yr in narrow sawfish and 15 yr in green sawfish (Dulvy et al. 2016).

An alternative, simpler explanation is that the shift in sawfish species composition and increasing trend in green sawfish reflects a change in logbook reporting practices by fishers. A total of 187 sawfish logbook records were independently verified, comprising 22% of all data used in the catch rate model. These data also showed a statistically significant increase in the proportion of green sawfish caught over time. However, the increase was smaller than would have been expected based on the logbook data (Fig. 4), indicating a bias towards the reporting of narrow sawfish. Aside from the independently verified data itself, little is known about how reporting practices might have changed through time. It is worth noting, however, that the 2 species are relatively easy to distinguish based on external morphology and size differences, with green sawfish on average 1.35 m larger than narrow sawfish (Fig. 5). Indeed, the large size (mean length = 4.08 m) of green sawfish and difficulty disentangling them means that their capture is often disruptive to fishing and unlikely to go unnoticed.

The available data are not able to clearly distinguish between these hypotheses, nor are they informative with respect to overall population status. They do, however, confirm that after 60 yr of trawling on the North West Shelf, both species of sawfish are still distributed throughout the most intensively fished area and are unlikely to have decreased in numbers over the last 2 decades.

4.2. Predictors of sawfish catch

In this study month, depth, and vessel were all found to significantly affect sawfish capture probability (Fig. 3). For month, the use of a cyclical spline term in the GAMLSS models revealed clear seasonal trends. We hypothesize that this may be related to an annual migration associated with parturition, as both species are known to use discrete coastal nursery areas. The lowest sawfish catch rates in the PTF were during October and November, corresponding with the timing of green sawfish pupping in the Ashburton Estuary (Morgan et al. 2015, 2017). The timing of narrow sawfish parturition is unknown in northwestern Australia, although it has been reported to occur around January in Queensland, Australia (Peverell 2005, Tobin et al. 2014).

No clear depth-related trends were evident for either species; however, the logbook data nonetheless provided useful insights into the depth preferences of adult fish. The widespread presence of sawfish within the boundaries of the PTF confirms that both species undergo a cross-shelf migration over their lifetime. Existing fisheries catch and survey data have previously alluded to this (Giles et al. 2004, Peverell 2005) but have typically been based on sparse records in shallow-water fisheries, often not identified to species. Herein, we show that both species disperse widely over the continental shelf to depths exceeding 100 m (Figs. 2 & 3, Fig. S2). Smalltooth sawfish have been shown to undertake similar ontogenetic shifts in habitat use in Florida, with females using deeper waters than males (Graham et al. 2022).

The finding of marked differences in vessel-specific catch in this study requires further investigation, but could be due to variable reporting practices. Alternatively, it may reflect technical differences, such as gear configuration or operational factors relating to fishing behavior (Northridge et al. 2017).

4.3. Conclusions

Australia's Sawfish and River Shark Multispecies Recovery Plan identifies the need to develop a quantitative framework to inform management and assess recovery (DoE 2015). The indices of abundance developed here are a key step towards achieving this objective and can be used to monitor trends in sawfish relative abundance, or in the development of quantitative population models. The outcomes of this work also serve to further highlight the importance of the North West Shelf for global sawfish conservation. Recent IUCN Red List reassessments maintained the Critically Endangered status of green sawfish (Harry et al. 2022), and uplisted the narrow sawfish to Critically Endangered (Haque et al. 2023). While contemporary and historic fisheries management measures have evidently been sufficient to allow sawfish populations to persist, the region is currently experiencing rapid development that is compounding pressures on these species, particularly through the loss of nursery habitat (Brocx & Semeniuk 2015, 2018). Further progress towards understanding sawfish population biology and ecology is urgently required in order to manage cumulative anthropogenic impacts on these globally significant populations.

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