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Post-release survival of two elasmobranchs, the eastern shovelnose ray (*Aptychotrema rostrata*) and the common stingaree (*Trygonoptera testacea*), discarded from a prawn trawl fishery in southern Queensland, Australia

Matthew J. Campbell[A,B,C], *Mark F. McLennan*[A], *Anthony J. Courtney*[A] and *Colin A. Simpfendorfer*[B]

[A]Queensland Department of Agriculture and Fisheries, Agri-Science Queensland, Ecosciences Precinct, GPO Box 267, Brisbane, Qld 4001, Australia.
[B]Centre for Sustainable Tropical Fisheries and Aquaculture, James Cook University, Townsville, Qld 4811, Australia.
[C]Corresponding author. Email: matthew.campbell@daf.qld.gov.au

Abstract. Post-trawl survival (PTS) is an important metric used in determining the ecological risk posed by prawn (shrimp) trawling on discarded elasmobranchs. Despite this, PTS of elasmobranchs is poorly understood. The present study quantified the PTS of two small batoids caught incidentally by prawn trawlers in southern Queensland, Australia, namely the common stingaree (*Trygonoptera testacea*) and the eastern shovelnose ray (*Aptychotrema rostrata*). Field studies using on-board tanks revealed that *A. rostrata* were more resilient to trawl capture and release than *T. testacea*. For both species, survival was found to increase with size, whereas increasing time on deck resulted in lower survival. Female *T. testacea* were found to be more resilient than males, and increased tow duration resulted in lower survival for *A. rostrata*. The mean ($\pm$s.e.m.) PTS for female and male *T. testacea* was 33.5 $\pm$ 6.0 and 17.3 $\pm$ 5.5% respectively, compared with a mean PTS for *A. rostrata* of 86.8 $\pm$ 3.2%. The survival estimates derived in the present study provide an insight into the effects of trawling on these species and will improve their ecological risk assessment and management.

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Introduction

Tropical prawn (or shrimp) trawling is recognised as a non-selective form of fishing (Griffiths *et al.* 2006) and accounts for 27.3% of the world's fisheries discards (Kelleher 2005). The discarded portion of prawn trawl catches is known to be composed of hundreds of species (Stobutzki *et al.* 2001; Courtney *et al.* 2006; Tonks *et al.* 2008) and includes species of conservation interest, such as sea turtles and some elasmobranchs (Watson and Seidel 1980; Robins-Troeger *et al.* 1995; Brewer *et al.* 1998; Wallace *et al.* 2010). This has led to the introduction of gear modifications to mitigate the interaction of these animals in many prawn trawl fisheries worldwide: turtle excluder devices (TEDs) and bycatch reduction devices (BRDs) have been used to reduce discards in many countries since the 1980s and numerous studies have reported their effects on catch rates of target and bycatch species (for a review, see Broadhurst 2000).

The introduction of TEDs has likely resulted in a reduction in the number of elasmobranchs landed by prawn trawl gear (Brewer *et al.* 2006). The elasmobranch component of prawn trawl bycatch has received increasing interest since the early 1990s (Molina and Cooke 2012). Elasmobranch life histories include late maturity, few offspring, long life spans and slow growth (Dulvy *et al.* 2008), making them vulnerable to overexploitation (Ellis *et al.* 2008). Although the introduction of TEDs has gone some way to decreasing the ecological risk posed to large elasmobranchs by prawn trawling (Kendall 1990; Fennessy 1994; Brewer *et al.* 1998), numerous studies have shown that the catch rates of smaller species (total length (TL) or disc width (DW) <1 m) remain unaffected (Brewer *et al.* 2006; Courtney *et al.* 2008; Raborn *et al.* 2012).

The introduction of TEDs in the eastern king prawn (EKP; *Melicertus plebejus*) fishery in southern Queensland, Australia, in 2001 has had little effect on the catch rates of small elasmobranchs (Kyne *et al.* 2002). The EKP fishery operates between the Swains Reefs (22°10′12″S, 152°41′45″E) in central Queensland and the New South Wales border (28°9′52″S, 153°32′51″E), with annual landings of ~3000 t, valued at approximately A$40 million. For management purposes, the fishery is partitioned into two separate components, the shallow water EKP fishery and the deep water EKP fishery, based on the 50 fathom (~91 m) bathymetric contour. Total discard rates from the shallow water fishery are much higher at 9.56 kg ha^{-1} (Courtney *et al.* 2006) than from the deep water fishery (1.11 kg ha^{-1}; Courtney *et al.* 2014). Research conducted in the early 2000s revealed that the discards in the shallow water fishery include high numbers of batoids (Kyne *et al.* 2002), most of which are small enough to pass through TEDs and into the codend due to the regulated bar spacing of 12 cm. Kyne *et al.* (2002) reported that two of the most common elasmobranchs found in the discarded portion of the shallow water EKP catch were the common stingaree (Urolophidae: *Trygonoptera testacea*) and the eastern shovelnose ray (Trygonorrhinidae: *Aptychotrema rostrata*).

T. testacea and *A. rostrata* are small (<40 cm DW and <1.2 m TL respectively) batoids endemic to Australia's east coast (Last *et al.* 2016). Both species are known to occur to depths of 90–100 m, feeding on benthic crustaceans (Kyne and Bennett 2002; Marshall *et al.* 2008). Despite their occurrence in catches, little is known about the life history of either species. As a result, a recent risk assessment conducted within the World Heritage-listed Great Barrier Reef Marine Park (GBRMP) categorised prawn trawling as posing a high ecological risk to both species (Pears *et al.* 2012). In this case, there was a high likelihood that the EKP fishery would exceed an acceptable level of interaction with these species within 20 years. Given that TEDs are ineffective at excluding *T. testacea* and *A. rostrata*, Pears *et al.* (2012) stated that a lack of post-trawl survival (PTS) estimates for these and other species represents the greatest source of uncertainty in assessing the effect of prawn trawling on elasmobranchs within, and adjacent to, the GBRMP.

The PTS of discarded elasmobranchs is poorly understood (Braccini *et al.* 2012; Oliver *et al.* 2015; Willems *et al.* 2016), despite its importance when assessing ecological risk (Stobutzki *et al.* 2002; Zhou *et al.* 2011). Ellis *et al.* (2017) recently reviewed 79 studies detailing the post-release survival of elasmobranchs and found most studies in the primary literature were conducted in pelagic longline fisheries, whereas 21 were trawl related (including beam trawl and scallop dredge) and only two studies were of prawn trawls (Fennessy 1994; Stobutzki *et al.* 2002). The paucity of PTS studies in trawl fisheries is most likely due to the cost and logistical constraints of field-based experiments needed to quantify post-release survival (Musyl *et al.* 2011; Benoît *et al.* 2013; Dapp *et al.* 2016). Most of the trawl-based field studies assessing the PTS of elasmobranchs have been conducted in northern hemisphere fish trawls (Revill *et al.* 2005; Rodríguez-Cabello *et al.* 2005; Mandelman *et al.* 2013) and have shown that survival is highly variable between species (Ellis *et al.* 2017). For example, in the Falkland Islands squid trawl fishery, Laptikhovsky (2004) found that the PTS of skates (Rajidae) ranged between 0% for *Bathyraja griseocauda* and *Bathyraja macloviana* to 71.4% for *Bathyraja albomaculata*. Several factors have been shown to affect the PTS of elasmobranchs, including catch weight (Mandelman and Farrington 2007*a*; Enever *et al.* 2010; Saygu and Deval 2014), air exposure (Benoît *et al.* 2010; Frick *et al.* 2010; Cicia *et al.* 2012), tow duration (Fennessy 1994; Enever *et al.* 2009; Saygu and Deval 2014), fish size (Enever *et al.* 2010; Benoît *et al.* 2013; Depestele *et al.* 2014), temperature (Cicia *et al.* 2012) and sex (Stobutzki *et al.* 2002; Laptikhovsky 2004; Enever *et al.* 2009). These and other factors have been shown to interact (Davis 2002), necessitating the use of controls, where possible, to isolate the effects of individual factors (Enever *et al.* 2010; Mandelman *et al.* 2013).

Retention of elasmobranchs has been prohibited in the EKP fishery since 2000, with fishers required to return all animals to the sea as soon as practicable. The fate of these discards is unknown. The aims of the present study were to assess the short-term (~3 days) PTS and to examine factors affecting the survival of the two most common elasmobranchs found in the catch, namely *T. testacea* and *A. rostrata*.

Materials and methods

This work was undertaken in accordance with General Fisheries Permit 186281, Marine Parks Permit QS2015/MAN322, Queensland Department of Fisheries and Agriculture Animal Ethics Approval Number CA2015/06/867 and James Cook University Ethics Approval Number A2236.

The PTS of *T. testacea* and *A. rostrata* was assessed during a dedicated experiment conducted off Southport (Fig. 1), southern Queensland (27°49′12″S, 153°30′E). This area was chosen for the survival experiment because past research (Courtney *et al.* 2007) indicated that both species occur in this area. Southport is a popular port, supporting at least 12 trawlers targeting EKPs year-round, although at least 200 vessels operate in the EKP fishery.

FV *C-Rainger*, a 15.6-m steel prawn trawler, was engaged to undertake trawls on known prawn grounds. *C-Rainger* used triple gear (see Broadhurst *et al.* 2013), consisting of three 12.8-m headline Florida flyer nets, spread by louvre-style otter boards. The body of each net was constructed from ~50-mm (2-inch) #36-ply polyethylene trawl mesh, whereas the codends were constructed from ~45-mm (1.75-inch) #60-ply polyethylene mesh. All nets were fitted with a top-shooting, single-grid hard TED with a bar space of 12 cm and a bigeye BRD as required by legislation. FRV *Tom Marshall* was chartered to undertake trawls to catch animals to control for a range of factors including trawl duration and time-on-deck. The *Tom Marshall* is a 14.5-m aluminium catamaran that used a single beam trawl towed from the stern. The beam net was a 6.5-m Florida flyer equipped with a top-shooter Wicks TED with a bar space of 12 cm and a fisheye BRD. The body of the net and the codend were constructed from the same materials used on the *C-Rainger*.

Experimental procedure

The PTS of *A. rostrata* and *T. testacea* was assessed during three separate sampling trips. The sampling trips were conducted over 5 days from 11 March 2016, over 5 days from 28 October 2016 and over 4 days from 15 December 2016. On the first night of each trip, an observer boarded the *C-Rainger* and collected samples under commercial trawling conditions. At the end of each trawl, sorting commenced: as elasmobranchs were found in the catch, they were tagged with a uniquely numbered streamer tag (PST13S; Hallprint, Adelaide, SA, Australia) and moved to an ~150-L holding tank, located on the deck adjacent to the sorting tray, and supplied with flow-through seawater via the vessel's deck hose. Tags were placed at the distal edge of the pectoral fin, level with the anterior gill slits. In order to assess the effect of air exposure, time on deck was recorded for each individual, quantified as the time, in minutes, between the

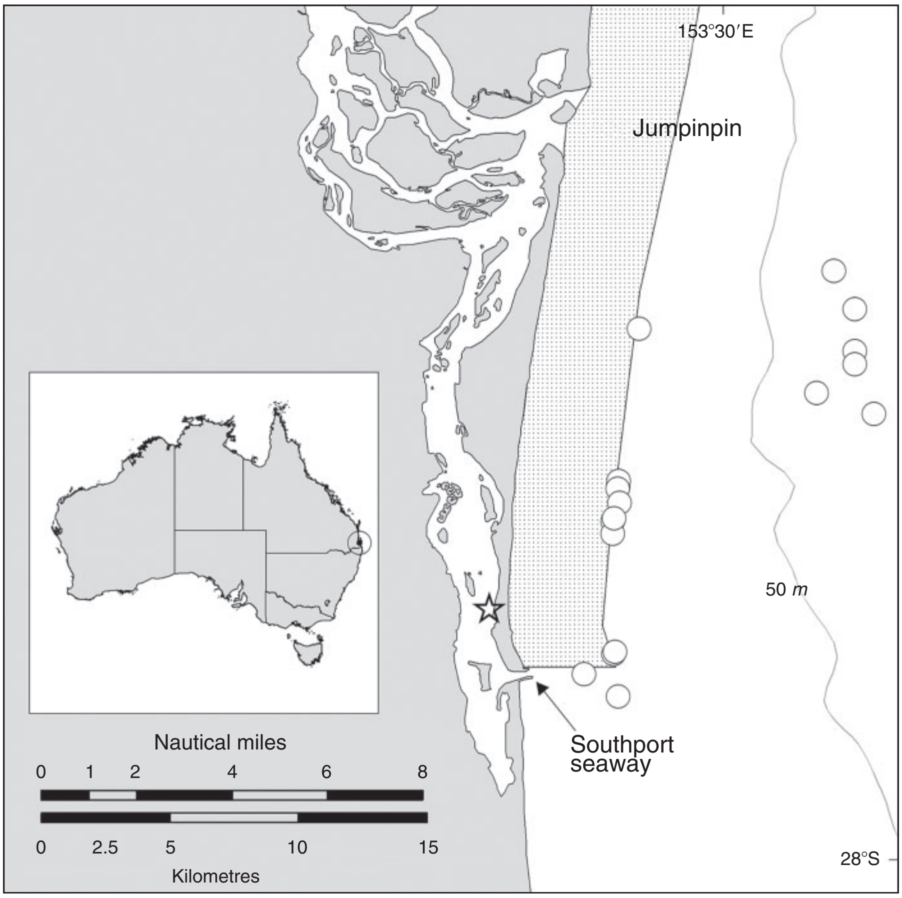

Fig. 1. Location of the post-release survival experiments conducted during 2016. The circles represent the starting point of each trawl undertaken by the *C-Rainger* and the star represents the anchorage used by the *Tom Marshall* where the animals were housed in the vessel's on-board tanks. The hatched area represents grounds closed to trawling.

codend being emptied onto the sorting tray and the time each individual was placed in the holding tank. A qualitative assessment of the condition of each animal, or condition index, was also recorded and followed Enever *et al.* (2009): 1, dead or nearly dead, no body movement, slight movement of spiracles; 2, limp wing movement, some spiracle movement; and 3, vigorous wing or body movement, rapid spiracle movement. The weight of the discards was quantified as the number of baskets of discards multiplied by 40 kg, the mean weight of a basket on the first night of trawling. Trawl duration, defined as the time between the end of winch away and the start of haul back, trawl depth and location were also recorded.

This process was repeated for all trawls on the first night until the cessation of fishing before dawn. Once the *C-Rainger* returned to port, live animals were transferred randomly to one of two 1400-L insulated plastic holding tanks aboard the *Tom Marshall*. This vessel was anchored in the Gold Coast Broadwater, close to the Southport Seaway, to ensure adequate water quality throughout the holding period (Fig. 1). Flow-through seawater was supplied to each container at a rate of $\sim$36 L min^{-1}. The tag number of any dead animals was recorded before the dead animals were stored in the vessel's on-board freezer for later examination. This process was repeated on the following night.

Also on the first sampling night, the *Tom Marshall* undertook 20 individual trawls using a 5-m beam. The objective of these trawls was to collect control animals of both species: short (10–20 min) trawls were conducted in reasonably shallow ($\sim$25 m) water, minimising factors known to affect PTS, such as total catch weight and trawl duration (Fennessy 1994; Enever *et al.* 2009). All individuals were tagged with a streamer tag before being placed in a 150-L insulated fish box supplied with flow-through seawater. As for the *C-Rainger*, time on deck was recorded for each individual to assess its effect on survival. At the cessation of trawl operations, the *Tom Marshall* returned to port and anchored in the Gold Coast Broadwater close to the Southport Seaway and all live animals were transferred randomly to one of the two 1400-L on-board holding tanks.

For all three sampling trips, the animals were monitored and, in accordance with previous studies (Mandelman and Farrington 2007*a*; Enever *et al.* 2009; Mandelman *et al.* 2013) and results reported by Wassenberg and Hill (1993), survival was assessed after 3 days (72 h). During that time, the tanks were inspected every 2 h and dead animals were removed and stored in the

Table 1. Number of individual *Trygonoptera testacea* and *Aptychotrema rostrata* caught by each vessel during the three post-release survival experiments conducted in 2016

Unless indicated otherwise, data are given as the mean ± s.e.m.

Trip	Night	FRV *Tom Marshall* (control animals)				FV *C-Rainger* (commercially trawled)			
		Number of trawls	Duration (min)	*A. rostrata* (*n*)	*T. testacea* (*n*)	Number of trawls	Duration (min)	*A. rostrata* (*n*)	*T. testacea* (*n*)
1	1	20	13.95 ± 0.71	13	35	3	158.17 ± 29.52	12	0
	2	–		–	–	4	145.44 ± 4.12	14	0
2	1	11	10.52 ± 0.24	20	57	5	80.61 ± 3.24	67	52
	2	–		–	–	3	86.74 ± 0.38	2	45
3	1	5	10.80 ± 0.20	4	27	3	66.00 ± 1.15	23	6

vessel's on-board freezer. For each animal, the TL for *A. rostrata* or DW for *T. testacea* (in mm) was recorded, along with the unique tag number. At the end of each sampling trip, all live animals were returned to the sea after the streamer tags were removed.

Statistical analyses

In accord with methods described by Campbell *et al.* (2014), PTS was quantified using generalised linear modelling (GLM) via a binomial distribution with a logit link function, where survival (a binary variable, with 0 = dead and 1 = alive) was the response variable. Separate models were developed for each species. For each model, several categorical factors were added to assess their effect on PTS: sampling trip (1, 2 or 3); control (0 = no, 1 = yes); and sex (male, female). Covariates for TL or DW, trawl duration, total discards and time on deck, transformed using either their natural logarithm or a square root transformation, were also tested. Statistical analyses were performed using R statistical software (R Foundation for Statistical Computing, Vienna, Austria, see https://www.R-project.org/, accessed 20 November 2017). Appropriate models were determined via the 'step' function, from the 'stats' package, which performs stepwise model selection using Akaike information criterion (AIC).

In accord with Enever *et al.* (2009), a second model was developed to determine the correlation, if any, between the condition index and PTS for each species. The only variable tested in this model was condition index as a categorical term with three levels (1, 2 or 3).

Results

The *C-Rainger* completed 18 trawls during the three sampling trips (Table 1), with trawl duration ranging from 64 to 217 min. All trawls were undertaken on trawl grounds that receive considerable fishing effort in depths between 27 and 54 m. Apart from *T. testacea* and *A. rostrata*, very few elasmobranchs were caught; however, six maskrays (*Neotrygon* spp.) and three coffin rays (*Hypnos monopterygius*) were caught in total and discarded alive immediately on capture.

The *Tom Marshall* completed 36 control trawls, ranging in duration from 10 to 20 min (Table 1). All trawls were conducted adjacent to the Southport Seaway (Fig. 1) in depths between 19 and 47 m (mean ± s.e.m., 27.2 ± 1.0 m). The only other elasmobranch caught by the *Tom Marshall* was the Kapala stingaree (*Urolophus kapalensis*): two individuals were caught during the second and third sampling trips (113 and 210 mm DW respectively), the larger of which aborted two pups (78 and 79 mm DW) during the sorting process. The two larger animals were tagged and retained, whereas the pups died soon after capture.

Trygonoptera testacea

In all, 187 *T. testacea* were assessed for PTS during the three experiments (Table 1), ranging in size between 75 and 245 mm DW (Fig. 2*a*). Animals caught on the *C-Rainger* were larger than those caught on the *Tom Marshall* (Fig. 2*a*; $t = 6.804$, $P < 0.001$). Females were more prevalent than males, with 109 and 73 caught respectively, and females were significantly larger than males (Fig. 2*b*; $t = 2.8776$, $P < 0.0$ 1). Of the 103 *T. testacea* caught on the *C-Rainger*, 68 (66%) died, as did 56 of the 84 (67%) caught on the *Tom Marshall*. *T. testacea* were more abundant on inshore grounds: none were captured by the *C-Rainger* on deeper (~50 m) trawl grounds during the first experiment (Fig. 1). For *T. testacea*, time on deck ranged between 1 and 28 min (mean ± s.d., 14.5 ± 7.1 min). Of the 187 *T. testacea* caught, 11 were given a condition index of 1, whereas 71 were given a score of 3 (Table 2). Generally, individuals were in good condition when placed in the holding tanks. Approximately half the animals contained throughout the experiment suffered abrasions to the ventral surface due to contact with the plastic holding tanks. Further, infection at the tag site was obvious in ~25% of the animals. However, survival was consistent across animals with and without abrasion injury or infection at the tag site.

Given no *T. testacea* were caught on the *C-Rainger* during the first sampling trip, it was excluded from the analysis. There was no significant difference ($P = 0.346$) in PTS between the second and third trips and, as such, data from the two trips were pooled. Survival of the control animals during the two trips did not differ significantly ($P = 0.603$) from that of animals caught on the *C-Rainger*, and trawl duration had no effect on PTS ($P = 0.154$). The natural logarithm of DW was the best predictor of survival ($P < 0.001$), with survival increasing with size (Fig. 3; $\beta = 8.598$, s.e. = 1.454). Both sex ($P = 0.051$) and time on deck ($P = 0.054$) had marginally significant effects on survival. The survival of females was higher than that of males ($\beta = 0.895$, s.e. = 0.461), whereas increasing time on deck was

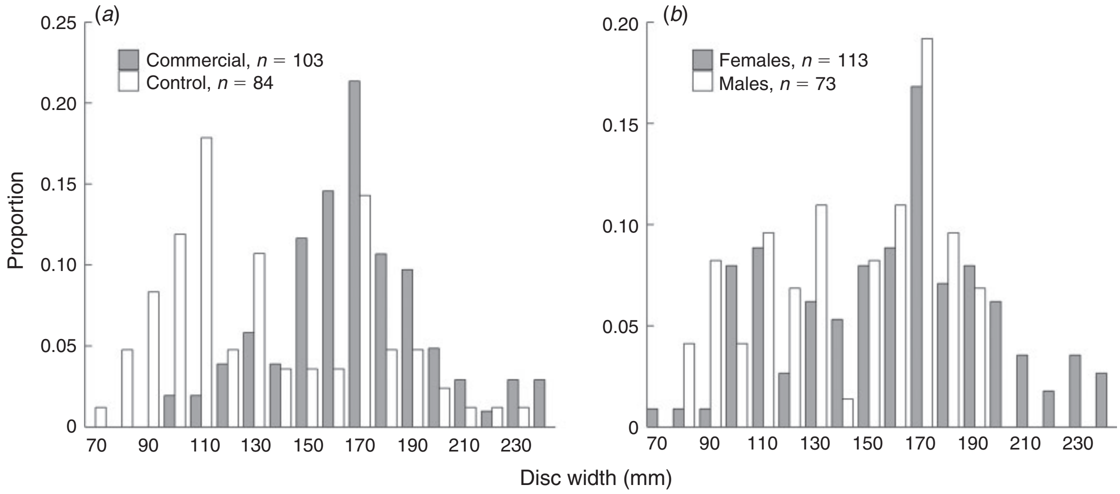

Fig. 2. Length–frequency distributions for 187 common stingarees (*Trygonoptera testacea*) caught during three post-release survival experiments as a function of (*a*) sampling type (control *v.* commercially trawled) and (*b*) sex. Note, sex was not recorded for five individuals.

Table 2. Post-trawl survival (PTS) of *Trygonoptera testacea* and *Aptychotrema rostrata* as a function of the condition index described by Enever *et al.* (2009)

Unless indicated otherwise, data are given as the mean ± s.e.m. The condition index was graded as follows: 1, dead or nearly dead, no body movement, slight movement of spiracles; 2, limp wing or wing movement, some spiracle movement; 3, vigorous wing or body movement, rapid spiracle movement

Condition index	*T. testacea*		*A. rostrata*	
	PTS (%)	*n*	PTS (%)	*n*
1	18.2 ± 11.6	11	50.0 ± 14.4	12
2	32.4 ± 4.6	105	85.1 ± 3.5	101
3	38.0 ± 5.8	71	90.5 ± 4.5	42

found to result in lower survival ($\beta = -0.109$, s.e. $= 0.057$). Given the confounding effect of females having a larger mean DW than males (Fig. 2*b*), a term representing the interaction of sex and size was added to the model and the two first-order terms were dropped. The final reduced model included only the interaction term and the time-on-deck covariate, both of which had a significant effect ($P < 0.001$) on PTS (Fig. 3). Mean (±s.e.m.) overall PTS for female and male *T. testacea* was 33.5 ± 6.0 and 17.3 ± 5.5% respectively. The condition index did not affect PTS despite a trend for higher survival with increasing levels of condition (Table 2).

Aptychotrema rostrata

Of the 155 *A. rostrata* assessed for PTS during the three experiments, 118 (~76%) were caught aboard the *C-Rainger* (Table 1). Of these, 24 (~20.3%) died, whereas only one of the 37 (2.7%) control animals caught on the *Tom Marshall* died. *A. rostrata* ranged in size between 166 and 555 mm TL (Fig. 4*a*) and animals caught on the *C-Rainger* were larger than those caught on the *Tom Marshall* ($t = 2.702$, $P = 0.009$). Females and males were equally represented in catches ($n = 78$ and $n = 77$ respectively) and their size did not differ significantly (Fig. 4*b*; $t = -0.321$, $P = 0.749$). Time on deck ranged between 1 and 63 min (mean ± s.d., 18.4 ± 12.0 min). Of the 155 *A. rostrata* caught, 12 were given a condition index of 1, 101 were given a score of 2 and 42 were given a score of 3 (Table 2). Very little physical damage was observed on the animals before they were placed into the holding tanks and, in contrast with *T. testacea*, infection at the tag site was not obvious on any *A. rostrata* held during the three sampling trips.

PTS did not differ significantly ($P = 0.470$) between sampling trips or between the control group ($P = 0.932$) and those caught in commercial trawls on the *C-Rainger*. The natural logarithm of TL was the best predictor of survival ($P = 0.011$), with survival increasing with TL ($\beta = 3.227$, s.e. $= 1.272$). Both the natural logarithm of trawl duration ($\beta = -1.206$, s.e. $= 0.587$) and time on deck ($\beta = -0.050$, s.e. $= 0.022$) were found to have a significant negative effect on survival ($P = 0.040$ and $P = 0.026$ respectively; Fig. 5). Mean (±s.e.m.) overall PTS for *A. rostrata* was 86.8 ± 3.2%. The condition index was found to have a significant ($P = 0.01$) positive effect on survival, suggesting that heathier animals on capture were more likely to survive (Table 2).

Discussion

These results represent the first short-term PTS estimates derived experimentally for elasmobranchs discarded from prawn trawls in the primary literature. Although two previous studies (Fennessy 1994; Stobutzki *et al.* 2002) discuss the at-vessel or immediate mortality of various sharks and rays captured during prawn trawl operations, the present study is the first to maintain animals in holding tanks for an extended period after capture in prawn trawls. The mean PTS of 86.8% for *A. rostrata* is at the upper bounds for batoids assessed using comparable methods (Ellis *et al.* 2017), whereas the survival of *T. testacea* was reasonably low, especially for males (17.3%).

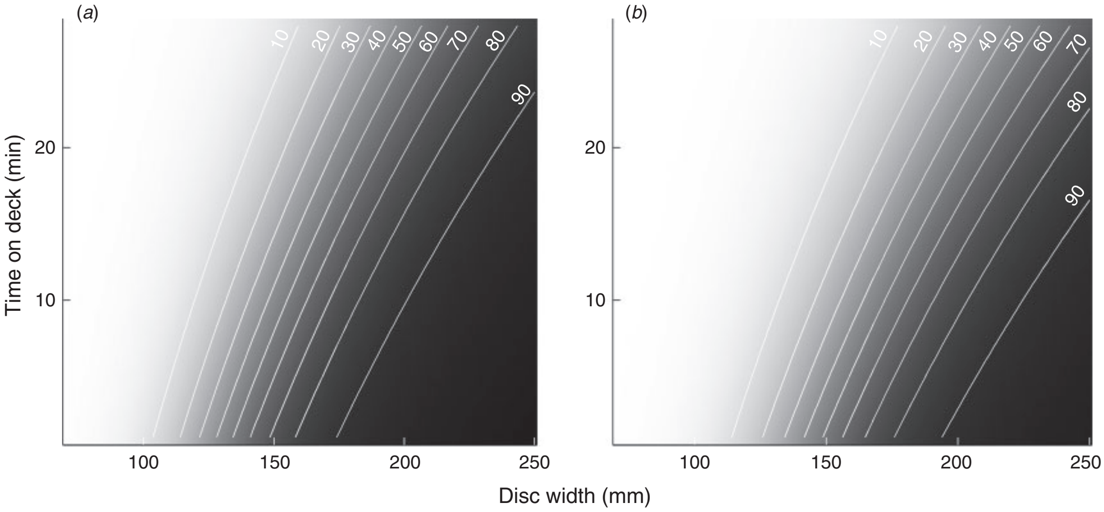

Fig. 3. Post-trawl survival of common stingarees (*Trygonoptera testacea*) as a function of disc width and time on deck for (*a*) females and (*b*) males caught during two sampling trips conducted in southern Queensland, Australia. The background shading represents increasing survival from 0% (white) to 100% (black) and the white contour lines indicate survival in 10% increments.

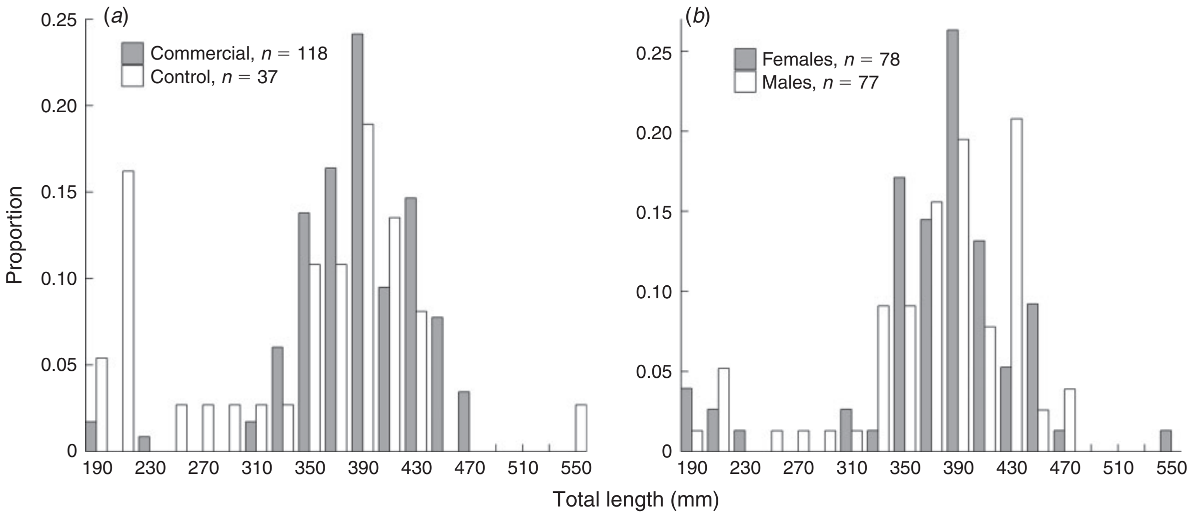

Fig. 4. Length–frequency distributions for 155 eastern shovelnose rays (*Aptychotrema rostrata*), caught during three post-release survival experiments, as a function of (*a*) sampling type (control *v.* commercially trawled) and (*b*) sex.

Species-specific differences are evident in previous studies assessing the PTS of elasmobranchs from trawl gear. For example, the PTS of thornback skate (*Raja clavata*) was 80.8% in the Turkish bottom trawl fishery, compared with 20.6% for the brown skate (*Raja miraletus*; Saygu and Deval 2014). Similarly, Enever *et al.* (2009) reported a PTS of 59% for *R. clavata*, compared with 33% for the cuckoo skate (*Leucoraja naevus*). In both studies, the higher PTS for *R. clavata* was attributed to its accentuated spines, which provide improved physical protection compared with other species. Differences in morphology were obvious in the two species assessed in the present study: *A. rostrata* are covered in fine denticles (Last *et al.* 2016), whereas *T. testacea* are smooth and soft to touch. This likely afforded *A. rostrata* more protection from injury and damage than *T. testacea* during trawl capture. Further, the morphology of *A. rostrata* provided protection against the physical abrasions associated with confinement-dependent factors affecting survival during the holding period, such as abrasion by the plastic tanks and piercing by the caudal sting of captive *T. testacea*. In contrast, a high proportion (~50%) of *T. testacea* had abrasions and injuries, particularly on their ventral surface, which appeared red and irritated at the end of each containment period. This issue may have been alleviated with the addition of substrate, allowing animals to bury and avoid abrasive contact with the plastic tanks. Further, ~25% of *T. testacea* showed signs of infection at the tag site, whereas no

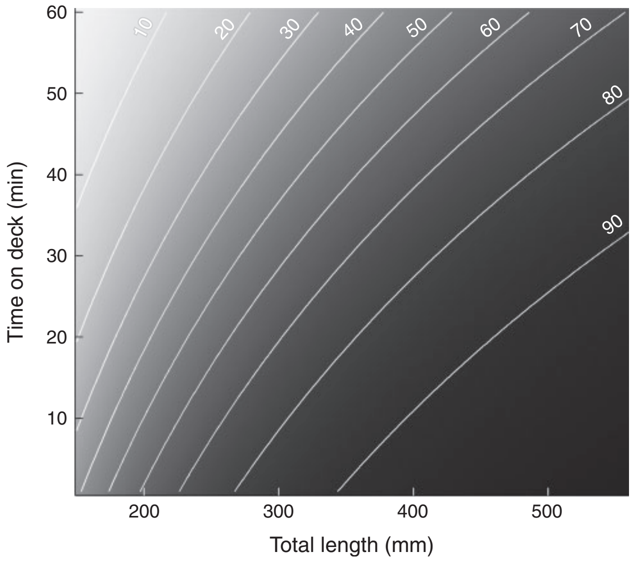

Fig. 5. Post-release survival of eastern shovelnose rays (*Aptychotrema rostrata*) as a function of total length and time on deck at the mean trawl duration of 146 min caught during three sampling trips conducted in southern Queensland, Australia. The background shading represents increasing survival from 0% (white) to 100% (black) and the white contour lines indicate survival in 10% increments.

A. rostrata appeared affected. The addition of antibiotic and antifungal ointments to the tag wounds, such as those used by Courtney *et al.* (2001), may have reduced any infection but were deemed unnecessary given that only short-term survival was assessed. Consequently, captivity in the holding tanks likely contributed to the low PTS of *T. testacea* and the estimates derived in the present study should be considered as minima for this reason.

The effect of holding animals in tanks is acknowledged as a source of bias when assessing PTS (Broadhurst *et al.* 2006; Mandelman and Farrington 2007*a*; Ellis *et al.* 2017). Ellis *et al.* (2017) suggest that captive stress, stocking densities and environmental conditions may affect post-release survival estimates. Despite this, the use of tanks to hold captive animals is the most common method used to determine PTS for elasmobranchs in field-based studies (e.g. Rodríguez-Cabello *et al.* 2005; Enever *et al.* 2009; Cicia *et al.* 2012). Apart from on-board tanks, researchers have used various methods to quantify the PTS of elasmobranchs, such as at-vessel mortality (e.g. Stobutzki *et al.* 2002), qualitative health assessments (e.g. Benoît *et al.* 2010, 2013), submerged holding pens located adjacent to fishing grounds (e.g. Mandelman and Farrington 2007*a*; Rulifson 2007; Mandelman *et al.* 2013), land-based tanks (e.g. Cicia *et al.* 2012; Mandelman and Farrington 2007*b*), blood physiology (Mandelman and Farrington 2007*a*, 2007*b*; Frick *et al.* 2010) and trawl simulation studies (e.g. Frick *et al.* 2010; Heard *et al.* 2014).

However, each of these methods has been shown to bias PTS estimates. For example, Frick *et al.* (2010) and Heard *et al.* (2014) tested the effects of crowding, air exposure and trawl duration on the survival of the three species of elasmobranch (i.e. *Heterodontus portusjacksoni*, *Mustelus antarcticus* and *Urolophus paucimaculatus*) in a laboratory and concluded that the survival estimates derived in each study cannot be extrapolated to animals caught in the wild due to the absence of additional stressors. At-vessel mortality has been used to assess PTS in prawn trawl fisheries (Fennessy 1994; Stobutzki *et al.* 2002); however, given the delayed effects of capture by trawl gear on survival (Van Beek *et al.* 1990; Wassenberg and Hill 1993; Kaiser and Spencer 1995), this method would have likely overestimated PTS for *T. testacea* given the small number of animals assessed with a condition index of 1 (Table 2). Passive acoustic telemetry, used by Dudgeon *et al.* (2013) to assess the site fidelity of the zebra shark (*Stegostoma fasciatum*) in south-east Queensland, was deemed unsuitable for assessing PTS in the present study given the time required to carefully perform invasive surgery at night on small animals (~10 cm DW) during commercial trawl conditions. Similarly, pop-up satellite archival tags (PSATs), such as those used by Campana *et al.* (2016) to estimate post-release survival of pelagic elasmobranchs, were unsuitable given the small size of *T. testacea* and *A. rostrata*.

Comparatively few *T. testacea* and *A. rostrata* were categorised as dead or nearly dead (Category 1; Table 2) on capture in the present study, with most mortalities occurring within 24 h of capture regardless of trawl type (control *v.* commercial). Condition index was found to be a poor predictor of survival for *T. testacea* (Table 2). Only 38% of *T. testacea* with a condition index score of 3 survived, reinforcing the inadequacy of at-vessel mortality as a reliable proxy for PTS for this species in particular, although this result may be compromised by the confinement-dependent effects discussed above. In contrast, 90.5% of *A. rostrata* with a condition index score of 3 survived, as did half the animals given a condition index score of 1. Given that only two staff were responsible for assessing condition, it may have been beneficial to increase the number of condition categories (Ellis *et al.* 2017). For example, Benoît *et al.* (2010) used four categories to assess survival from a fish trawl in Canada. In the present study, the survival of animals presenting with a condition index score of 1 had the most variable PTS (Table 2) and, as such, this portion of the study may have benefited from an extra category describing poor health, such as that described by Benoît *et al.* (2010).

The housing of animals in on-board tanks precludes interaction with predators and scavengers after release (e.g. Enever *et al.* 2009; Mandelman *et al.* 2013). Therefore, PTS derived using this method may be overestimated. In the present study, bull sharks (*Carcharhinus leucas*) were observed feeding on the discards from the *C-Rainger* while the catch was being sorted. Further, blue swimmer crabs (*Portunus armatus*) and three-spot crabs (*Portunus sanguinolentus*) were regularly caught as bycatch throughout the three sampling trips, both of which are known scavengers caught by trap fishers in south-east Queensland. Further research is required to determine the effect of predation and scavenging on the PTS of *T. testacea* and *A. rostrata*.

For both species, the size of the individual was the best predictor of PTS, with larger animals more likely to survive (Figs 3, 5). This is consistent with previous studies for elasmobranchs (Stobutzki *et al.* 2002; Depestele *et al.* 2014; Saygu and Deval 2014). For example, Saygu and Deval (2014) found that larger thornback skates (*R. clavata*) and brown skates

(*R. miraletus*) were more likely to survive at least 48 h after capture in a Turkish trawl fishery. Similarly, Enever *et al.* (2010) reported that health score on capture increased with the size of skates (*L. naevus*, *Raja microocellata*, *Raja brachyura*, *R. clavata and Raja montagui*) caught by fish trawls in the UK, resulting in higher PTS. The size-related difference in survival has been attributed to reduced resilience of smaller animals to fatigue and injury (Davis 2002; Benoît *et al.* 2013). Benoît *et al.* (2013) suggested that smaller animals are less likely to survive capture because of a susceptibility to hypoxia due to a higher mass-specific metabolic rate and a higher energy cost for breathing.

Air exposure is an important predictor of PTS (Davis 2002; Broadhurst *et al.* 2006; International Council for the Exploration of the Sea 2014) and is a function of the time required to process the catch (Davis 2002). In the present study, time on deck affected the PTS of both *T. testacea* (Fig. 3) and *A. rostrata* (Fig. 5). Time on deck reflected catch weight and trawl duration: increasing trawl duration resulted in higher catch weights and longer sorting times. The crew of the *C-Rainger* sorted the catch by making a space ($\sim$0.75 m^2) on the sorting tray before filling that space with a small amount of catch. Prawns were removed to buckets before any elasmobranchs were selected and passed to the observer for tagging. This process was repeated until all catch had been processed. The tagging procedure took $\sim$5–10 s and, as such, the time-on-deck metric used in the present study is representative of commercial operations in the EKP fishery. A reduction in PTS resulting from increased air exposure is consistent with previous studies. Cicia *et al.* (2012) and Frick *et al.* (2010) respectively reported lower survival for little skate (*Leucoraja erinacea*) and gummy sharks (*M. antarcticus*) after increased levels of air exposure during laboratory-based experiments. Field studies (Benoît *et al.* 2010, 2012) found reduced survival for skates (Rajidae) with increasing exposure to air after capture by fish trawls in Canada. Cicia *et al.* (2012) provide a detailed description of the physiological response to air exposure and, along with Mandelman *et al.* (2013), showed that elevated temperature gradients between air and water exacerbate the effects of air exposure. However, the temperature gradient was reasonably constant across the three sampling trips in the present study, prohibiting analysis of this metric.

Female *T. testacea* were more likely to survive than males. Studies that have found sex-specific PTS in elasmobranchs invariably report that the survival of females is higher (Laptikhovsky 2004; Enever *et al.* 2009; Mandelman *et al.* 2013). Enever *et al.* (2009) and Mandelman *et al.* (2013) suggest higher survival in females is a result of the thicker skin that provides protection against biting males during copulation. Mandelman *et al.* (2013) hypothesise that the presence of claspers may lead to injuries for males. In the present study, female *T. testacea* were larger (Fig. 2), confounding the effect of sex, given the GLM indicated that size was the best predictor of PTS in this species. Similarly, Stobutzki *et al.* (2002) found that the immediate PTS of female batoids (*Neotrygon leylandi*, *Maculabatis toshi* and *Gymnura australis*) caught in a northern Australian prawn trawl fishery was higher, noting that the males of most elasmobranchs are smaller. Interestingly, the PTS of *A. rostrata* was not sex specific, nor were there significant size differences between the sexes of this species. These results suggest that sex-specific differences in PTS in other studies (e.g. Stobutzki *et al.* 2002) may have been due to the larger size of the females rather than any morphological differences between sexes.

Tow duration had a negative effect on the PTS of *A. rostrata*. Where measured, increased tow duration has resulted in lower PTS for elasmobranchs (e.g. Mandelman and Farrington 2007*a*; Enever *et al.* 2010; Mandelman *et al.* 2013). For example, Fennessy (1994) reported that shorter tows resulted in increased PTS of backwater butterfly rays (*Gymnura natalensis*) in a South African prawn trawl fishery. However, an inability to quantify the exact time an animal enters the trawl makes interpretation of tow duration data difficult (Mandelman *et al.* 2013). As discussed previously, the results from the present study show that there is correlation between tow duration, time on deck and catch weight. Tow duration was a better predictor of PTS due to difficulties in measuring catch weight accurately. Further, tow duration is a metric familiar to prawn trawl operators, facilitating better communication of results to stakeholders. These results suggest that fishers should limit the duration of trawls where these species are present, resulting in lower catch weights and shorter sorting times, thereby increasing survival rates. This is particularly the case for the shallow water EKP fishery, where bycatch catch rates are high and catch sizes are large (Courtney *et al.* 2006).

In conclusion, TEDs are effective at reducing the catch of turtles from prawn trawls: however, current TED regulations regarding bar spacing allow the retention of a large number of smaller elasmobranchs in prawn trawl fisheries worldwide. It is therefore prudent to assess PTS of these animals when determining the ecological risk posed by prawn trawling. Field-based experiments conducted as part of the present study have shown that *A. rostrata* are more resilient to trawl capture and release than *T. testacea*. To ensure maximum PTS for both species, fishers should limit the duration of trawls where these species are present and fishers should prioritise removing elasmobranchs from the catch and return them to the sea as quickly as possible

In excess of 45 species of elasmobranch have the potential to interact with the EKP fishery in southern Queensland (Last and Stevens 2009). Of these, the scalloped hammerhead (*Sphyrna lewini*) is considered to be 'endangered' according to the IUCN Red List (Baum *et al.* 2007), whereas the Endeavour skate (*Dentiraja endeavouri*) and the bluegrey carpetshark (*Brachaelurus colcloughi*) are classified as 'vulnerable' (Kyne 2011; Kyne *et al.* 2015). Consequently, assessing the catch and the PTS of these and other species is necessary to ensure that current levels of fishing effort in the EKP fishery are sustainable in the longer term.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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