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The impact of turtle excluder devices and bycatch reduction devices on diverse tropical marine communities in Australia's northern prawn trawl fishery

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Abstract

In 2001, paired-trawl comparisons were made during prawn trawl operations to assess the effect of turtle excluder devices and bycatch reduction devices on a range of species groups caught in tropical Australia. This study is one of the first to evaluate the commercial use of these devices in a tropical fishery. Nets with a combination of a turtle excluder device and bycatch reduction device reduced the catches of turtles by 99%, seasnakes by 5%, sharks by 17.7%, rays by 36.3%, large sponges by 85.3%, and small bycatch by 8%, however, these results were largely attributable to the influence of the turtle excluder devices. Nets with both devices also reduced the catch of commercially important prawns by 6%, but the proportion of soft and damaged prawns was reduced by 41%. The combination of these devices had no measurable impact on catches of any of the three byproduct species groups: *Thenus* spp. (Moreton Bay bugs), *Teuthoidea* spp. (squid) and *Amusium pleuronectes* (scallops). Turtles excluder devices reduced the numbers of larger sharks and rays (>1 m) by 86% and 94%, respectively. They did not reduce the total number of sawfish caught, but did reduce the number of the most commonly caught species – the narrow sawfish (*Anoxypristis cuspidata*) – by 73.3%. Upward- and downward-excluding turtle excluder devices performed about equally for most species groups, although upward excluders were more effective for sharks and less effective for large sponges. The performance of BRDs was poor for most groups and could be improved by using them in more effective positions such as closer to the codend catch. The use of these devices is a major step towards ensuring the long-term conservation of many species, especially endangered sea turtles and vulnerable elasmobranchs. As fishers become more experienced in their use, we are optimistic that the fishery's impact on bycatch will reduce even further.

Keywords: Turtle excluder devices; Bycatch reduction devices; Bycatch; Prawn trawls; Shrimp trawls; Sea turtles; Sea snakes; Sawfish

1. Introduction

Until recently, the primary management aim of harvest fisheries was to maximise sustainable yields of the target species. Relatively little attention was paid to minimising the effects of fishing on the broader ecosystem. However, better informed science, new legislation and market drivers have forced or influenced changes in fishing practices in many countries (Hall and Mainprize, 2005). These changes often require ecosystem-based approaches to fishery management to ensure that all species, communities and habitats are impacted in a way that does not compromise their long-term viability (e.g. Kaiser et al., 2000; Ward, 2000; Babcock et al., 2005).

One of the most effective ways to minimise the broader ecological impacts of harvest fisheries is to improve the selectivity of fishing gear (e.g. Robertson, 1984; Liu et al., 1985; Alverson et al., 1994; Briggs et al., 1999). Although this is not a new strategy, recent pressures have accelerated the development and use of new and more selective techniques. Examples include the introduction of turtle excluder devices (TEDs) and bycatch reduction devices (BRDs) in prawn and shrimp trawl fisheries in many countries (e.g. Watson et al., 1986; Isaksen et al., 1992; Hall and Mainprize, 2005; Courtney et al., 2006), the use of semi-pelagic fish trawls to reduce bycatch and minimise impacts on

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benthic habitats (Brewer et al., 1996), the use of streamer lines and underwater bait-setting devices in pelagic longline fisheries to reduce the catch of seabirds (Melvin et al., 2004), and acoustic devices to reduce dolphin catches in gill nets (Kraus et al., 1997; Kastelein et al., 2000; Bordino et al., 2002).

The world's fisheries catch between about 6.8 million tonnes (Kelleher, 2004) and 20 million tonnes (FAO, 1999) of bycatch each year. Demersal prawn (shrimp) trawl fisheries are responsible for about one-third of that (Alverson et al., 1994). These catches are usually dominated by fish and invertebrate species that are returned to the water either dead or dying (Wassenberg and Hill, 1989; Hill and Wassenberg, 1990, 2000; Alverson, 1997; FAO, 2002). Vulnerable or protected species such as sea turtles and sea snakes are also components of this bycatch in tropical prawn trawl fisheries. Consequently, some governments have also placed tight restrictions on prawn trawl fisheries to reduce their impacts on these species. For example, the United States has banned imports of prawns (shrimp) from countries not using TEDs as effectively as in the USA (Hall and Mainprize, 2005). Australia's Northern Prawn Fishery (NPF) has also banned the take of shark products to eliminate the practice of shark finning (Brewer et al., in press).

The NPF extends across about 6000 km of the northern Australian coastline (Fig. 1) and catches about 8300 tonnes of prawns per year (Perdrau and Garvey, 2004). However, a wide variety of unwanted species (bycatch), including sea turtles, sea snakes, sharks, rays, sawfish, sponges, other megabenthos, and small fish and invertebrates are caught during fishing operations (Stobutzki et al., 2001). The ratio of the bycatch to prawns has been estimated to range between 8:1 and 21:1 (Pender et al., 1992; Brewer et al., 1998). In 2000, this fishery introduced the compulsory use of a specific suite of TEDs and BRDs. TEDs must have rigid or semi-rigid bars, a maximum bar spacing of 120 mm and have an escape opening of at least 700 mm. BRDs must be either the Bigeye BRD (subsequently removed from the list of approved BRD designs), the Square-mesh panel BRD, the Fisheye BRD, Square-mesh codend BRD, a radial escape section (RES) BRD, or a modified TED which can be used instead of a TED and BRD combination (Eayrs et al., 1997; Brewer et al., 1998; Watson et al., 1993) (Fig. 2a–e). However, it was unclear what impact the introduction of TEDs and BRDs would have on the broad range of species groups (target, byproduct and bycatch) caught by this fishery.

Previous assessments of TEDs and BRDs have been made in northern Australia but not during commercial fishing conditions (Brewer et al., 1997, 1998). Other assessments of these devices have also been made in other regions of the world (see review by Broadhurst, 2000). Some in situ assessments have included expert assistance to maximise gear performance (e.g. Eayrs and Day, 2004a,b). The main aim of this project was to assess the catching performance of nets fitted with TEDs and BRDs during commercial operations in the NPF, on all major bycatch and commercially important species groups. It provides one of the first published assessments of the impacts of these devices on a wide variety of bycatch species in a tropical prawn trawl fishery.

2. Materials and methods

2.1. General approach

To demonstrate the effect of the introduction of TEDs and BRDs, a team of scientific observers collected data for an assessment of the performance of these gears during a single fishing season in 2001. This assessment aimed to be representative of the industry's use of TEDs and BRDs and gave fishers 18 months to

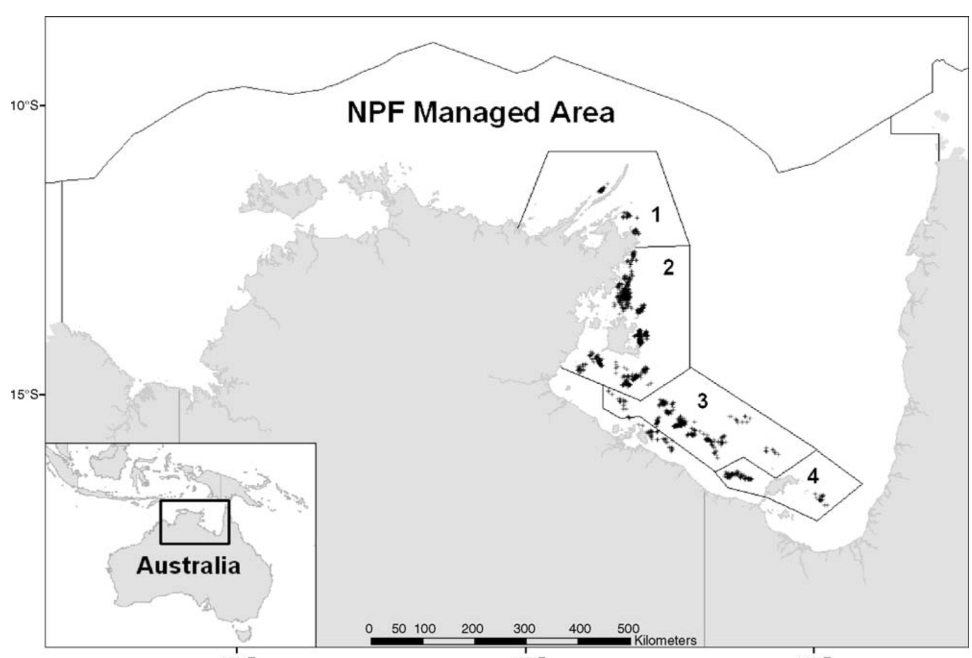

Fig. 1. Data collection locations. Map of Northern Australia showing the Northern Prawn Fishery managed area, the four sampling regions and 1612 trawl sites used in the 2001 performance assessment of TEDs and BRDs.

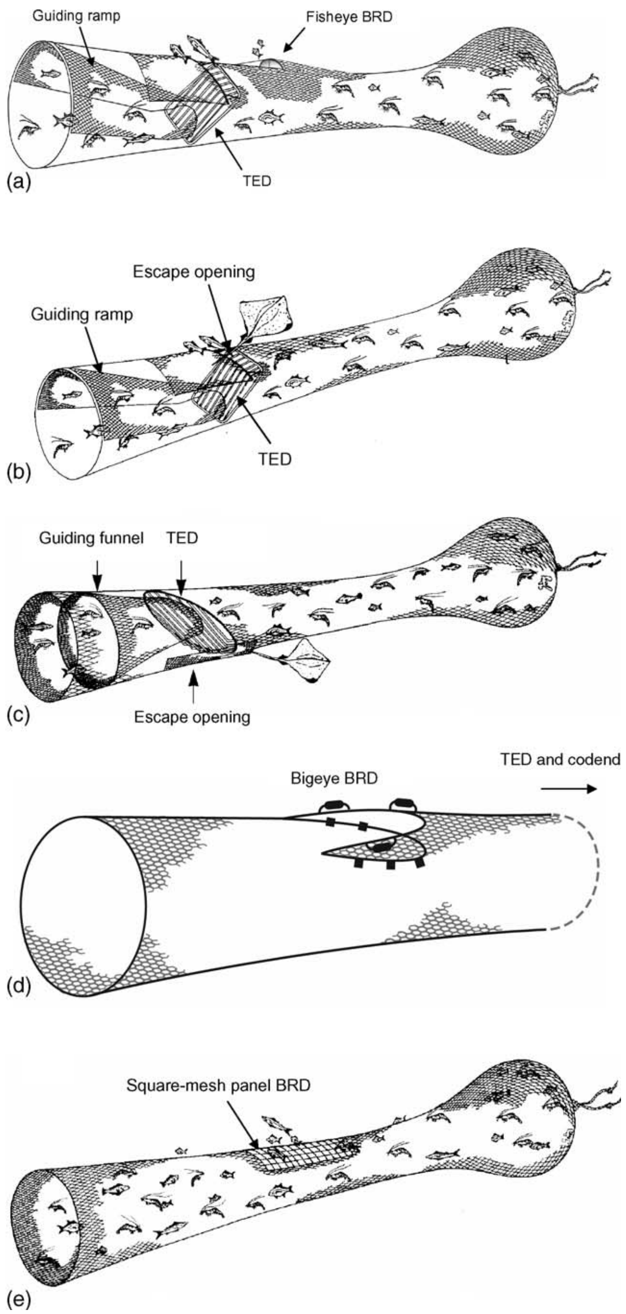

Fig. 2. TED and BRD configurations. Diagrams of the TED and BRD configurations assessed during the 2001 performance assessment program, including (a) NPF trawl codend of the current legal net fitted with an upward-excluding TED and BRD; (b) upward-excluding TED in a TED-only net; (c) downward-excluding TED in a TED-only net; (d) Bigeye BRD in a BRD-only net; (e) Square-mesh panel BRD in a BRD-only net. All TED and BRD configurations and their relative positions encountered during the study are not represented. Figures courtesy of Steve Eayrs, Australian Maritime College and Lee Crosswell, CSIRO.

adapt their fishing skills with these devices after the gear changes became mandatory.

The NPF currently has two distinct fishing seasons: an autumn fishing season (April–June, targeting *Penaeus merguiensis* and *Pterocarpus indicus*) and a spring fishing season (August–November, targeting *Penaeus semisulcatus*, *Penaeus esculentus*, *Metapenaeus endeavouri*, *Metapenaeus ensis* and *P. indicus*). The spring fishing season has typically been associated with longer night-time tows and large amounts of bycatch. This bycatch includes large catches of small fish and invertebrates, and a wide variety of other species groups, such as sea turtles and sea snakes, that have a low likelihood of survival after being towed in nets for long periods (Brewer et al., 1998; Stobutzki et al., 2001). This TED and BRD assessment was implemented during the 2001 night-time spring fishing season to coincide with the fishery's highest impact on these bycatch groups.

Data were collected on most species groups captured by the fishery. These were placed in the following categories that reflect the main concerns of fishery stakeholders for vulnerable or endangered species, key ecological species or communities, and the commercial catch: sea turtles, sea snakes, elasmobranchs (sharks, rays and sawfish), large sponges (greater than 300 mm), small bycatch (all other bycatch less than about 300 mm in length), commercially important prawns, and commercially important byproduct ('byproduct' hereafter).

2.2. Experimental design

In 2001, the 23 NPF vessels that took part in the study towed twin Florida Flyer prawn trawl nets from a boom on each side of the vessel, usually for four trawls each of 3–4 h in duration per night. The study assessed TED and BRD performance during the spring fishing season (August–November) when there is a daytime ban on trawling between 08:00 h and 18:00 h in the Gulf of Carpentaria.

The experimental design aimed to compare catches between nets with different gear configurations, based on preliminary power analyses. As a null hypothesis, all comparisons assumed that there was no difference between catches from port and starboard nets, regardless of the inclusion of TEDs and/or BRDs. The nets without a TED or BRD installed were used as the experimental controls and towed from one randomly assigned side of each vessel. The treatment nets towed from the opposite side of the boat were either:

- TED + BRD nets (the current legal configuration)—to measure the effect of the two devices in combination (Fig. 2a);
- TED-only nets—to measure the separate effect of the TEDs (Fig. 2b and c); or
- BRD-only nets—to measure the separate effect of the BRDs (Fig. 2d and e).

TEDs were categorised as either upward- or downward-excluding, depending on the position of the escape opening (Fig. 2b and c). These are used by 47% and 53% of the NPF fleet, respectively. The most common shapes of TEDs used in the fleet are curved at one end (38%), oval (28%) or rectangular (23%). BRDs were used with either an upward- or downward-excluding TED and were categorised by their general design: either a Bigeye BRD (Fig. 2d) or Square-mesh panel BRD (Fig. 2e). In 2001, most of the NPF fleet used the Bigeye BRD (78%), but some used the Square-mesh panel BRD (12%) and the Fisheye BRD (5%) (Eayrs et al., 1997), although the Fisheye BRD was not used on any vessels involved in this assessment.

A range of factors was included in the experimental design to ensure that the data would be representative of normal NPF commercial operations. To ensure the data accurately reflected the variability between vessels in the NPF fleet (including vessel size, trawl configuration, skipper's fishing and gear-rigging ability, and the types of TED and BRD used) each of the five scientific observers boarded a different vessel approximately every 2 weeks during the entire 3 months of the spring fishing season. The design also aimed to spread the coverage of observer effort between the major fishing areas in the Gulf of Carpentaria.

2.3. Field sampling

While on board each vessel the observers collected data on the total weights of commercially important prawns, byproduct and small bycatch groups; counts (and weights where possible) of all sea turtles, sea snakes, elasmobranchs and large sponges; TED and BRD descriptions and configurations; trawl-gear configurations; trawl log data (location, date, time, etc.); abiotic data on weather and sea conditions. They also recorded unusual or irregular events such as net damage, TED blockages or changes to the normal fishing regime that could affect catch differences between the two nets. Due to concurrent and conflicting sampling requirements, not all species groups were processed from all trawls. When most of the species groups were caught together, an evolving prioritisation process was used to ensure that data were collected for all species groups throughout the study.

The two tiger prawn species (*P. semisulcatus* and *P. esculentus*) are not separated during commercial operations, neither are the two endeavour prawns (*M. endeavouri* and *M. ensis*). Consequently, impacts on commercially important prawns are reported as 'total prawns', 'tiger prawns' and 'endeavour prawns'. 'Total prawns' include all tiger prawns, endeavour prawns, banana prawns (*P. merguiensis* and *P. indicus*) and king prawns (*Penaeus latisulcatus* and *Penaeus longistylus*). The small portion of 'soft and damaged' prawns (3.97% of tiger prawns, 0.94% of endeavour prawns) was treated and analysed as a separate category. Data were collected separately for three of the most valuable groups of byproduct (retained but not targeted): (i) *Thenus indicus* and *Theileria orientalis* (Moreton Bay bugs), (ii) several species of Teuthoidea (squid) and (iii) *Amusium pleuronectes* (scallops). Other species of byproduct are retained less frequently and were not included in this study.

Once the prawns, byproduct and selected bycatch had been removed, the small bycatch from each net was weighed separately by accumulating the weights of manageable amounts (30–40 kg at any one time). Other bycatch groups were identified, counted and measured (carapace length for sea turtles, vent length and weight for sea snakes, total length and weight for elasmobranchs and weight for large sponges).

2.4. Data analyses

The field data were entered into an Oracle database specifically designed to integrate the data for this project. Trawls were excluded from the analyses where breakages, holes in the nets, or other events may have affected catches but were not related to the presence of TEDs or BRDs. The components of the catch data were analysed differently depending on whether weights or counts were measured, or if the catch group was rarely caught.

2.4.1. Weight data: model 1

A log transformation was carried out to normalize the errors of each treatment for weight data from prawns, byproduct and the small bycatch. Each trawl comparison consisted of two nets towed simultaneously. The weights collected from the two nets of a vessel were paired to eliminate trawl-to-trawl variation by analysing the differences between the log weights of the treatment and control nets (D in model 1). These differences were analysed with a linear model with vessels considered as a random effect.

Model 1—for weight data: define D to be

$$D = [\log(\text{treatment net wt}) - \log(\text{control net wt})].$$

Then we assumed that the differences (D) were normally distributed with a mean (μ_D) and variance (σ_D^2):

$$D \sim N(\mu_D, \sigma_D^2),$$

and the linear model for the mean expectation of D as

$$\log(E(D)) = \text{comparison}(i) + \text{vessel}(j) + \text{covariates};$$

where $E(D)$ is the expected value of D.

A 'covariates' term was used in model 1 to account for the potential variable influence of region, duration and presence of sponges in catches of the most abundant bycatch groups.

The region term is a categorisation of the prawn target area into four distinct areas (Fig. 1). Trawl duration was measured in minutes. If sponges were observed in a net, then the sponge covariate was given the value 1, otherwise it had the value 0. This term aimed to examine the possible effect of sponges being caught on the TED and increasing the exclusion of other groups. However, when analysing the actual count data for sponges, the sponge covariate was not included in the model. Weather was recorded, but was not included as a covariate because of a lack of a useful contrast between sea states in the data.

The most important terms in these analyses are the treatment factors (all categories and combinations of TED and/or BRD). The vessel effect and covariates were included to assess their influence on capture rates and the effectiveness of the gear configurations, but are not reported in detail. The least-squares means for the differences D when multiplied by 100 gave approximate estimates of the percentage difference in weight between the treatment net and the control net.

2.4.2. Count data: model 2

Count data were recorded consistently for species or species groups that were rarer, often large and more conspicuous, or of special interest or significance. These included sea turtles, sea snakes, elasmobranchs and large sponges. Model 2 was also applied to broader elasmobranch groups to assess more general trends, including sharks 1 m or more in length, sharks less than or equal to 1 m in length, rays 1 m or more in width and rays less than or equal to 1 m in width. For these (mostly rarer) groups, the power to detect effects of the vessel, region and sponge catch on their catch rates is very low, so is not presented. However, an assessment of the effectiveness of TEDs and BRDs could be obtained by restricting the data set to those trawls where at least one animal was caught, making a paired comparison between a treatment and control net.

The larger species groups (sea turtles, elasmobranchs and large sponges) were likely to have highest exclusion through TEDs and less or no exclusion through the BRDs. This was confirmed in a preliminary analysis and a later analysis of the combined BRD's effect on catches of these groups. As many of these species were caught in low numbers, a separate analysis was undertaken on any pairs of nets that had a TED in one net and no TED in the other, regardless of the presence of BRDs.

For species that were counted, a binomial model with a fixed probability of capture was used with the response variable being "number caught". Given that an animal is caught, we view the side on which it is caught as a binomial outcome, with probability p for the treatment side (TED and/or BRD) and $1 - p$ for the control net side. A natural null hypothesis is then $p = 1/2$, implying no exclusion by the treatment net. Since the counts were often quite low, this null hypothesis was then tested by an exact analysis of binomial frequencies ('exact binomial test') against a two-sided alternative. For cases where the counts were higher, a simpler χ^2-test would have sufficed, but the exact binomial test was used as a slightly more robust option (Fleiss, 1981).

If the null hypothesis is retained, the treatment is not shown to have reduced the bycatch. If the null hypothesis is rejected, it indicates that the treatment has an effect. Whether the effect is to increase or decrease the conditional probability of capture is then clear from the data, and percentages can be calculated.

2.4.3. Logistic regression of length data

This model describes the relationship between the size of sharks (total length) and rays (disc width) and their rates of capture in nets containing a TED, and control nets. A standard logistic regression model was used to relate the probability that the animal is caught in the TED-net side to the size of the animal. Two separate models were fitted—one for all sharks combined and the other for all rays.

If p is the probability that an animal is caught on the TED side, the logistic regression model expresses this probability as a function of size. Assuming both nets were equally exposed to incoming animals, n was taken to be the expected number of animals to which each of the two nets were exposed and e as the exclusion rate of the TED. The expected number of animals caught in each side is then

No TED	TED
n	$n(1-e)$

Hence the probability that a caught animal was found in the TED net is

$$p = \frac{n(1-e)}{n + n(1-e)}$$

which, for example, is 0.5 only if $e = 0$ and the TED is ineffective. Solving this equation for e gives

$$e = \frac{1-2p}{1-p}$$

which then relates the exclusion rate of the TED to the probability of capture on the TED side, which the logistic regression model has, in turn, related to the size of the animal. The logistic regression fitting process also allows an estimate of pointwise confidence intervals, which can be transferred to the exclusion rates.

Model 1 (weight data) was fitted using PROC MIXED (SAS, 2001). For model 2, the exact binomial tests were undertaken in S-PLUS (function binom.test). PROC GENMOD (SAS, 2001) was used for analyses of sea snake captures.

3. Results

Data were collected from a total of 1612 trawl comparisons (3224 nets sampled over 442 nights of trawling) from 23 different vessels. TED designs used by these vessels varied widely, with no two vessels having the same design. These included 14 downward-excluding TEDs and 9 upward-excluding TEDs; 7 made of stainless steel and 16 of aluminium; 11 elliptical, 7 U-shaped and 5 rectangular TEDs; 4 with guiding funnels, 5 with guiding panels and 14 with neither. TED angles varied from 40 to 72° with a mean of 51.8 (S.E. = 1.8) and bar spacings varied from 95 to 120 mm with a mean of 110.2 (S.E. = 1.5). All TED escape openings were at least 700 mm wide, as specified in the fishery regulations although their actual size varied in order to match the width of the TED. Seventeen vessels used loose covers of trawl netting over the TED escape opening, and these varied in their length of overhang from 2 to 33 meshes, with a mean of 14 (S.E. = 1.7) meshes.

3.1. Sea turtles

A total of 1240 trawl comparisons was examined for sea turtles and 84 individuals were recorded from 84 separate trawls (Table 1). Of the 51 sea turtles identified to species, 52.9% were Olive Ridley sea turtles (*Lepidochelys olivacea*), 25.5% Flatback sea turtles (*Natator depressa*), 7.8% Loggerhead sea turtles (*Caretta caretta*) and 3.9% Green sea turtles (*Chelonia mydas*).

In trawls to compare the catches of nets with TEDs to control nets, 66 of the 67 sea turtles were caught in the control nets. No sea turtles were caught in nets with a TED + BRD gear combination. Only one turtle was caught in a net with a TED only. In this case, a juvenile Flatback sea turtle (28 cm carapace length) was captured in the net in front of an upward-excluding TED and released alive. The data suggest that TEDs are very effective (about 99%) at excluding sea turtles from NPF prawn trawl nets fitted with TEDs (Table 2). There was no difference in the number of sea turtles caught between BRD-only nets and control nets.

Table 1
Sample sizes used for analysing the effects of TEDs and BRDs on catches in the Northern Prawn Fishery

Catch group	Total nets (*n*)	Sample size		Nets per treatment (*n*)							
		kg	*n*	TED + BRD	TED net	BRD only	Control net	Upward-excluding TED	Downward-excluding TED	Bigeye BRD	Square-mesh panel BRD
Sea turtles #	168		84	33	67	17	84	22	45	–	–
Sea snakes	864		774	214	172	46	432	–	–	38	8
Elasmobranchs #											
Sharks	1750		3965	434	727	148	875	115	178	–	–
Rays	1820		3608	459	787	123	910	144	184	–	–
Sawfish	64		33	17	26	6	32	2	7	–	–
Large sponges #	678		1923	150	392	97	339	127	115	–	–
Small bycatch	1406	373021		324	267	112	703	108	159	65	47
Prawns											
Total prawns (all commercial species)	2126	93389		538	351	174	1063	143	208	100	74
Tiger prawns	2108	60125		530	351	173	1054	143	208	99	74
Tiger prawns (soft and damaged)	1396	2385		325	216	157	698	108	108	88	69
Endeavour prawns	1938	30325		483	320	166	969	129	191	16	16
Endeavour prawns (soft and damaged)	336	284		92	44	32	168	23	21	17	15
Byproduct											
Thenus spp.	562	444		135	100	46	281	45	55	27	19
Teuthoidea spp.	268	520		65	43	26	134	31	12	16	10
Amusium pleuronectes	66	28		18	15	–	33	–	15	–	–

#, species groups where the ‘TED net’ analyses included any net with a TED (TED + BRD or TED only). –, no comparison made.

Table 2
The percentage change in catches and significance levels due to the effects of TEDs and BRDs

Catch group	Treatment						
	TED + BRD	TED net	BRD only	Upward-excluding TED	Downward-excluding TED	Bigeye BRD	Square-mesh panel BRD
Sea turtles #	-100^{***}	-99.0^{**}	ns	-99.0^{***}	-100^{***}	–	–
Sea snakes	-5.0^{*}	ns	ns	–	–	ns	ns
Elasmobranchs #							
Sharks	-17.7^{***}	-13.3^{***}	-16.7^{***}	-20.4^{***}	-8.8^{***}	–	–
Rays	-36.3^{***}	-31.3^{***}	ns	-26.9^{***}	-34.8^{***}	–	–
Sawfish	ns	ns	ns	ns	ns	–	–
Large sponges #	-85.3^{***}	-86.3^{***}	ns	-81.6^{***}	-95.9^{***}	–	–
Small bycatch	-8.0^{***}	-7.9^{***}	ns	ns	-8.9^{*}	ns	ns
Prawns							
Total prawns (all commercial species)	-6.0^{***}	-5.8^{***}	-4.4^{*}	ns	-5.7^{*}	-4.2^{**}	ns
Tiger prawns	-6.5^{***}	-6.7^{***}	-3.8^{*}	-6.3^{*}	-6.3^{*}	-3.9^{*}	ns
Tiger prawns (soft and damaged)	-41.6^{***}	-55.1^{***}	ns	-35.8^{**}	-63.2^{***}	ns	ns
Endeavour prawns	-5.0^{**}	ns	ns	ns	ns	ns	ns
Endeavour prawns (soft and damaged)	-40.9^{**}	-44.4^{**}	ns	ns	ns	ns	ns
Byproduct							
Thenus spp.	ns	ns	ns	ns	ns	ns	ns
Teuthoidea spp.	ns	ns	ns	ns	ns	ns	ns
Amusium pleuronectes	ns	ns	–	–	ns	–	–

#, species groups where the ‘TED net’ analyses included any net with a TED (TED + BRD or TED only). ns = no significant difference between comparisons; –, no comparison made. Significance levels: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

3.2. Sea snakes

A total of 774 individual sea snakes of 12 species was recorded from 432 of 1427 trawl comparisons (Table 1). The highest catches were 11 sea snakes in 1 trawl (2 nets) and 6 sea snakes from a single net. *Hydrophis elegans* (Elegant sea snake) was the most abundant species (39.3%), followed by *Lapemis hardwickii* (Short sea snake) (18.0%) and *Disteira major* (Olive-headed sea snake) (16.0%). The other species caught were *Astrotia stokesii* (Stokes' sea snake) (7.9%), *Hydrophis ornatus* (Ornate sea snake) (6.8%), *Aipysurus laevis* (Olive sea snake) (6.4%), *Hoplodactylus pacificus* (Large-headed sea snake) (3.6%), *Aipysurus eydouxii* (Spine-tailed sea snake) (3.0%), *Acalyptophis peronii* (Horned sea snake) (2.3%), *A. duboisii* (Dubois' sea snake) (1.0%), *Disteria kingii* (Spectacled sea snake) (0.5%) and the rarest was *Hydrophis macdowelli* (Small-headed sea snake), of which only one (0.13%) was caught.

There was a small difference between gear types in the sea snake numbers caught: an estimated 5% fewer in nets with TED + BRD gear than in control nets, but nets with a TED only or BRD only did not differ from control nets (Table 2). Both the Bigeye BRD and Square-mesh panel BRD caught slightly fewer sea snakes than the control net, but the differences were not statistically significant (Tables 1 and 2).

3.3. Elasmobranchs—sharks, rays and sawfish

A total of 1084 trawl comparisons was examined for elasmobranchs. Of the 7606 individuals recorded 3965 were sharks, 3608 were rays and 33 were sawfish (Table 1). The 98% of elasmobranchs identified constituted 36 species of 14 families. Most of the individuals caught (64%) were from five species: *Carcharhinus dussumieri* (White cheek shark), *Carcharhinus tilstoni* (Australian blacktip shark), *Rhynchobatus djiddensis* (White-spotted guitarfish), *Gymnura australis* (Australian butterfly ray) and *Himantura toshi* (Black-spotted whipray). Compared to the total number of sharks caught in control nets, significantly fewer were caught in TED + BRD nets (17.7%), any nets with a TED (13.3%) and nets with only BRDs installed (16.7%) (Table 2). However, only one species – *C. tilstoni* – demonstrated a significant difference (23.8%) between nets with a BRD only and the control net. The exclusion rates of sharks was higher with upward-excluding TEDs (20.4%) than with downward-excluding TEDs (8.8%) (Table 2).

Rays also showed a significant reduction in numbers caught in TED + BRD nets (36.3%) and any nets with a TED (31.3%) (Table 2). However, the numbers of rays in BRD-only nets were no different from the control net for all rays combined. There was little difference in exclusion rates of rays between upward- and downward-excluding TEDs (26.9% and 34.8%, respectively) (Table 2).

Overall, sawfishes were rare in catches. Of the 33 animals caught, 25 were the *Anoxypristis cuspidata* (Narrow sawfish). There was no significant difference between the treatment nets and the control net in the total number of sawfish caught (Table 2). However, there was a significant difference ($p < 0.05$) in *A. cuspidata* catches: 73.3% fewer in nets with a TED ($n = 4$) than in nets without a TED ($n = 15$).

The impact of TEDs on the larger species was demonstrated by separate analyses of large and small sharks and rays. Of the large sharks (>1 m long), 86% fewer were caught in nets with TEDs than in nets without TEDs, and of the large rays (>1 m wide), 94% fewer were caught in nets with TEDs. For smaller animals the differences were much smaller: only 4.9% fewer small sharks were caught in nets fitted with TEDs than in control nets, and 25% fewer small rays (less than 1 m) were caught in nets with TEDs. These differences in the exclusion rates of different-sized rays and sharks are also depicted by the curves fitted by a logistic regression model of animal lengths (Fig. 3). They describe a much higher exclusion rate for large sharks (Fig. 3a) and large rays (Fig. 3b) than smaller individuals, and describe a major change in the exclusion rates of large animals greater than 1 m in size.

3.4. Large sponges

A total of 1240 trawl comparisons was examined for large sponges and 1923 individual sponges were recorded from 339

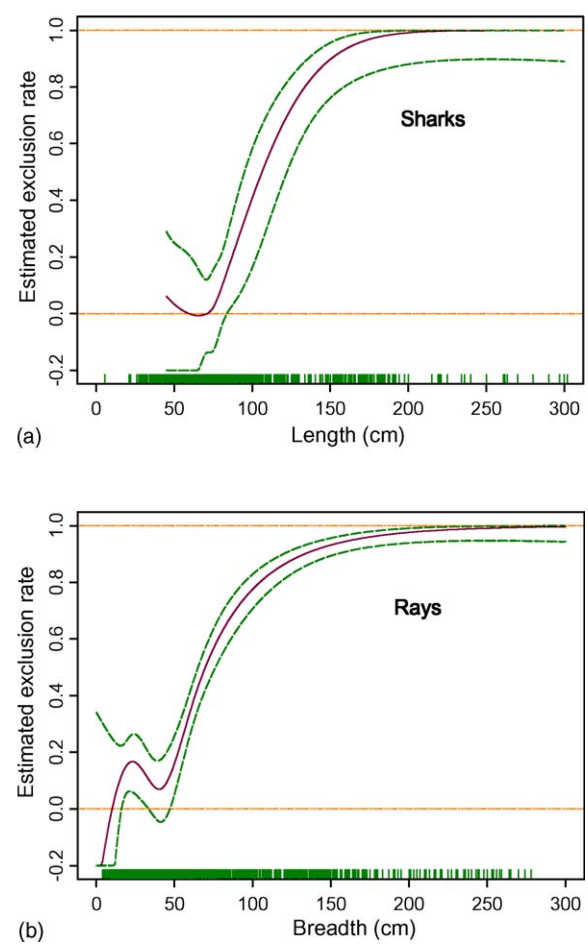

Fig. 3. Exclusion rates for different sized elasmobranchs. Logistic regression model outputs for (a) sharks and (b) rays showing the estimated exclusion rates for different-sized animals (smooth curve) with 95% confidence intervals. The sizes available for these analyses are indicated along the *X*-axis by a 'rug' of single lines, one line for each animal.

separate trawls (Table 1). Compared to the number of large sponges caught in control nets, nets with both TEDs and BRDs caught 85.3% fewer (Table 2), and nets with only TEDs caught 86.3% fewer. Upward-excluding TEDs removed 81.6% from the trawl catch, while downward-excluding TEDs excluded 95.9%. BRDs had no impact on exclusion of large sponges from catches.

3.5. Small bycatch

A total of 373,021 kg of small bycatch was weighed and analysed (Table 1). These data provided comparisons from 703 pairs of trawls (1406 nets), which constituted 43.6% of all trawls in the study. An average weight of 207.7 kg (S.E. ± 4.91) of small bycatch was recorded from the control nets (no TED or BRD).

The combination of TEDs and BRDs reduced the weight of small bycatch by 8% (Table 2). This result appears to be almost entirely attributable to the influence of TEDs, which produced a similar result on their own (7.9% catch reduction). Upward-excluding TEDs made no measurable difference to small bycatch, although downward-excluding TEDs reduced small bycatch by 8.9%. The BRDs trialed in this study (Bigeye BRD and Square-mesh panel BRD) also had no effect on catches of small bycatch.

The impacts of TEDs and BRDs on catches of small bycatch were affected by the trawl duration ($p < 0.05$) and geographical region ($p < 0.05$): catches were larger from longer duration trawls and the mean catches in region 4 (West and East Mornington Is., Fig. 1) were larger than elsewhere.

3.6. Commercially important prawns

Data were collected on commercially important prawns during most trawl comparisons −1 063 of 1 612 trawls (65.9%)—although the number of comparisons for each species group varied (Table 1). A total of 93,389 kg was processed. Most were tiger prawns (60,125 kg) and endeavour prawns (30,325 kg); less than 0.3% (270 kg) were other penaeid species.

The impact of using a TED + BRD in the 2001 spring fishing season included an average 6% reduction in the total prawn catch. This reduction was slightly higher for tiger prawns (6.5%) and slightly lower for endeavour prawns (5.0%). With a TED only, the reductions in catches were similar for total prawns (5.8%) and tiger prawns (6.7%), but there was no reduction in catches of endeavour prawns. However, the catch of soft and damaged prawns was substantially reduced with a TED and BRD net (41.6% fewer in the case of tiger prawns and 40.9% fewer endeavour prawns) and also with a TED-only net (55.1% fewer tiger prawns and 44.4% fewer endeavour prawns) (Table 2).

Upward-excluding TEDs had no effect on catches of total prawns, but reduced tiger prawn catches by 6.3% (Table 2). They also resulted in 35.8% fewer soft and damaged tiger prawns in catches. Downward-excluding TEDs reduced catches of total prawns by 5.7% and tiger prawns by 6.3% and were responsible for 63.2% fewer soft and damaged tiger prawns. Endeavour prawn catches were maintained regardless of whether the TED was an upward- or downward-excluding design.

Nets with BRDs only reduced total prawn catches by 4.4% (Table 2). This is reflected in a reduction of 3.8% for tiger prawn catches, although there was no change in endeavour prawn catches or the proportion of soft and damaged prawns. Of the two BRDs assessed in this study, only the Bigeye affected prawn catches: a 4.2% reduction in total prawn catches and 3.9% reduction for tiger prawns. There was no change in prawn catches in nets using Square-mesh panel BRDs.

Catches of most prawn groups were not affected by the influence of the covariates (duration of the trawl, region fished or presence of sponges in catches). Soft and damaged tiger prawns were the exception: catches were significantly larger from (i) shorter duration trawls ($p < 0.05$), and (ii) the presence of large sponges ($p < 0.05$). The reduction in catches of soft and damaged tiger prawns changed from 28.1% to 39.7% due to the presence of large sponges in the control net compared to the TED and BRD net.

3.7. Byproduct

Data were collected on commercially important byproduct during 281 of 1612 trawl comparisons (17.4%) for *Thenus* spp., 134 trawl comparisons (8.3%) for Teuthoidea spp., and 33 trawl comparisons (2%) for *A. pleuronectes* (Table 1). A total of 444 kg of *T. indicus* and *T. orientalis*, 520 kg of *Teuthoidea* spp. and 28 kg of *A. pleuronectes* was processed.

The use of TEDs and BRDs had no measurable impact on the catch weights of *Thenus* spp., *Teuthoidea* spp. or *A. pleuronectes* (Table 2). The results were the same for both upward- and downward-excluding TEDs and for BRDs. None of the catches of the three byproduct groups was affected by the covariates.

4. Discussion

The mandatory introduction of TEDs and BRDs in the NPF fleet in 2000 was designed to reduce the impact of trawling on bycatch in this fishery. The results presented in this paper show that they have had a considerable effect on catches but that the reduction in impacts varies between species. TEDs exclude most large animals that cannot fit through the bars, including most species of sharks and rays and large sessile invertebrates. Sawfish appear to be the only exception to this. Smaller animals are also excluded from trawls by TEDs, probably due to a behavioural avoidance response when the TED is approached or encountered, leading to their exclusion through the escape opening.

Most BRDs rely on the behavioural escape response of fish, sea snakes and other animals. However, the BRDs used in the fishery during this study functioned poorly compared to similar BRDs in other fisheries (e.g. Brewer et al., 1998; Broadhurst, 2000). This highlights a need to improve the way that BRDs operate in the fishery, by better understanding how species react to fishing gear and the best positional placement of BRDs in the net.

4.1. Sea turtles

Most sea turtles species today are either endangered or vulnerable. Consequently, they have been the focus of much attention in the trawl fisheries where they are caught, and frequently drown (Poiner and Harris, 1996). Their life-history strategy of having naturally low survival rates and a long sub-adult phase (time to maturity) has made them highly vulnerable to anthropogenic impacts. In Australia, the original impetus for bycatch reduction was partly the public's concern about the impact of trawling on sea turtles (Robins-Troeger et al., 1995).

In the current assessment, both the upward- and downward-excluding TEDs were extremely effective at preventing sea turtle capture. Similar results have been reported in other studies (Watson et al., 1993; Robins-Troeger et al., 1995; Brewer et al., 1997, 1998; Campbell, 1998, 1999; Salini et al., 2000; Day and Eayrs, 2001). This study included comparisons across a range of regions, vessels and TEDs, where the rigging of these devices vary.

Prawn trawling is now an insignificant source of mortality for sea turtle populations in northern Australia. In 1989–1990, Poiner and Harris (1996) estimated that 10–18% of 5000–6000 sea turtles caught in prawn trawls drowned and another 50% were damaged or in poor condition when landed. The incidence of capture in non-TED nets during this study (0.056 sea turtles per trawl >3 h) was close to the capture rate of 0.051 described earlier by Poiner and Harris (1996). With the current range of TED devices in use, the catch has declined to less than 0.5% of the numbers previously caught. At the same time, the overall level of fishing effort has been reduced to about 50,000 trawls per year – half that of 1989–1990 – and the incidence of capture is now about 0.0006 per trawl >3 h. Based on these data, the number of sea turtles caught by the entire fleet in 2002 would be less than 50, of which fewer than 10 would be likely to drown and up to 15 would be harmed in some way.

4.2. Sea snakes

Sea snakes are air-breathing reptiles that feed mainly on bottom-dwelling fishes such as gobies and eels (Fry et al., 2001). All species are fairly long-lived (up to 11 years) (Ward, 2001), give birth to only a few young each year, and are thus unlikely to be able to sustain substantial additional mortality from fishing. Sea snakes have been common in NPF catches: an estimated catch of one per trawl before TEDs and BRDs were introduced (Stobutzki et al., 2001). The 1991 catch total was estimated as 120,000 individuals (Wassenberg et al., 1994). The 14 species are protected under Australian legislation and total sea snake numbers caught must now be recorded in the logbooks of NPF vessels.

The 5% reduction in total sea snake catches in our study where fishers used TEDs and BRDs, is significantly less than the 50% reduction recorded when Square-mesh panel BRDs were used in an experiment in the NPF (Brewer et al., 1998). The other BRDs used in both the current and previous study did not reduce the catches of sea snakes. The Square-mesh panel BRD was not widely used in the current study, but the number of trawls with this device was much the same as in Brewer et al. (1998). This suggests that there may have been a difference in the positioning or configuration of this BRD that resulted in a large difference in the exclusion rates in the two studies. These other studies indicate that effective use of TEDs or specific BRDs, such as the Square-mesh panel BRD or Square-mesh codend BRD, could significantly reduce the impact of trawl fisheries on sea snakes.

Three species – *H. pacificus* (Pacific sea snake), *Aipysurus laevis* (Olive sea snake) and *Astrotia stokesii* (Stoke's sea snake) – appear to be more at risk than the other species (Milton, 2001), through higher vulnerability to trawling and/or poor capacity to sustain fishing mortality. A significant improvement in the performance of BRDs, could, by reducing the impact of the fishery on sea snakes, lower their level of risk dramatically. This type of outcome was also achieved in the Gulf of California for an endangered sciaenid fish (*Totoaba macdonaldii*) where an 81% exclusion rate was achieved by using a radial escape section (RES) BRD (Garcia-Caudillo et al., 2000).

4.3. Elasmobranchs—sharks, rays and sawfish

The Indo-west Pacific region has a very diverse elasmobranch fauna, and in Australia's NPF, 56 elasmobranch species (19 families) have been recorded in trawl catches (Stobutzki et al., 2001). There is widespread concern over the impact of fishing on elasmobranchs. Their biology (slow growth rates, low natural mortality and fecundity) implies their populations may not be able to sustain fishing practices designed for more productive teleosts and invertebrates (Stevens et al., 2000), although their resilience varies between species (Walker and Hislop, 1998).

The introduction of TEDs and BRDs in 2000, in combination with the ban on retention of elasmobranch products in 2001, has greatly reduced the impact of the NPF on elasmobranch populations. The high exclusion rates for large sharks (86%), large rays (94%) and the most commonly caught sawfish (*A. cuspidata*, 73.3%) includes more than half of the species recorded in this region. However, the NPF has not significantly reduced catches of many of the small species, which dominate the elasmobranch bycatch (Stobutzki et al., 2001). These results are consistent with three other studies: Brewer et al. (1997) and Day and Eayrs (2001), also in the Australia's Northern Prawn Fishery, reported an 88% and 77.8% reduction, respectively, in the catches of large sharks and rays (>5 kg) from nets with TEDs.

In contrast, BRDs are often designed to enable smaller fish to escape by swimming through strategically designed openings. However, the Bigeye BRD, with its 1 m-wide hole in the top of the net fitted forward of the usual TED position, could allow quite large elasmobranchs to escape, and this may explain the 16.7% exclusion of sharks (and in particular, *C. tilstoni*) from nets fitted with BRDs. It is unlikely that other BRDs used in this fishery (e.g. Square-mesh panel BRD and Fisheye BRD) would allow many elasmobranchs (especially rays and sawfish) to escape, given their relatively small escape openings (Fig. 2a and e).

Sawfish have been overfished in many parts of the world and are no longer found off the coasts of many countries (Simpfendorfer, 2000). Northern Australian waters are one of the last areas where significant populations still exist. However, in this region they have been impacted by both trawl and gillnet fisheries for many years. Little is known about their distribution, ecology and population status but their life history characteristics and the tendency for their saw to entangle in nets make them particularly vulnerable to fishing mortality. Modelling of sawfish population dynamics suggests that their populations may take decades to recover from large reductions (Simpfendorfer, 2000).

This study shows that only *A. cuspidata* is excluded by TEDs and that almost 20% of the sawfish caught in trawl nets are caught due to their saws getting tangled in the body of net forward of the TED. Hence sawfish exclusion from trawls may be improved by lining or replacing the section of the net ahead of the TED with a different material (e.g. canvas, fine metal mesh or tough flexible plastic). Other sawfish species caught more rarely in NPF catches (*Pristis pectinata*, *P. clavata*, *P. microdon* and *P. zjisron*) were shown by Stobutzki et al. (2002) to be in the group of elasmobranchs least likely to be sustainable in the bycatch of the NPF. As this group is one of high international and national concern, the fishery may need to examine other alternative methods to reduce its impact on these species (e.g. targeted spatial or temporal closures).

Five of the "relatively high-risk" elasmobranch species identified by Stobutzki et al. (2002) (*A. cuspidata*, *Himantura uarnak*, *Pastinachus sephen*, *Rhina ancylostoma* and *Rhynchobatus typus*) are usually encountered by trawls as large individuals and hence are also likely to have been excluded from most trawl catches since the introduction of TEDs. At least five other "relatively high-risk", species that grow to large sizes (*Dasyatis thetidis*, *Himantura fai*, *Himantura granulata*, *Negaprion acutidens* and *Urogymnus asperrimus*) are also likely to have had significant reductions in fishing mortality. Given the different exclusion rates of elasmobranch species to TEDs, and the changes in catch rates, the assessment of the relative risk to these species from the fishery (Stobutzki et al., 2002) should be re-examined.

4.4. Large sponges

This study is the only published assessment of the impacts of TEDs or BRDs on catches of sponges, and demonstrates their effective exclusion (85.3%) by TEDs for this bycatch group. Large sponges are usually heavy, highly porous and negatively buoyant. It is reasonable to expect that downward-excluding TEDs remove large sponges from catches more effectively than upward-excluding TEDs. The current study found that the exclusion rates for large sponges of downward-excluding TEDs (95.9%) were higher than of upward excluders (81.6%), although both forms of TED were highly effective.

The study has also demonstrated that, in almost all cases there is no relationship between catches of large sponges and the exclusion rates of animals through nets fitted with TEDs and BRDs. It is likely that large sponges are excluded before they block the TED and affect the exclusion rates of other species. Although most large sponges are excluded by TEDs, the small species of sponges (<120 mm diameter) are likely to pass through the bars of TEDs into the net and consequently be poorly excluded (although not measured in this study).

Nothing is known of the fate of the sponges that are excluded from trawls. It is not known whether sponges can survive being uprooted from the substrate and immediate dumping back onto the sea bed. Nor is it known how their fate affects the conservation of demersal communities. There may be little difference between a dislodged sponge being dumped back through the TED or after being taken in the catch. However, the difference may be greater for the many other species that have a commensal relationship with the sponge.

4.5. Small bycatch

Although BRDs were introduced into the NPF to minimise catches of the hundreds of smaller species of teleosts and invertebrates (Brewer et al., 1998), the 8% exclusion of the small bycatch was attributed mainly to TEDs rather than BRDs, and in particular, the downward-excluding TEDs. This same pattern was seen for all prawns combined. These small species should all pass through the TED and into the codend where they are either caught or escape through BRDs. Their catch exclusion through the TED is most likely to result from either, (i) poor construction, installation or tuning of the TED (Eayrs and Day, 2004a,b), for example, a poorly functioning escape flap, or (ii) blockages on the TED (usually by large animals) causing smaller animals to be diverted through the TED escape opening. The negatively buoyant, less mobile benthic species (prawns, benthic fish and invertebrates) may be particularly vulnerable to these issues for downward-excluding TEDs.

Prawn trawls are designed to catch small animals and it is difficult to exclude similar sized bycatch species such as fish and crabs. Exclusion of large animals such as turtles or large elasmobranchs is far easier using TEDs. BRDs have been designed to increase escapement of small bycatch species, by directing them to positions that take advantage of their natural escape responses. For example, the Fisheye BRD and Square-mesh panel BRD are usually positioned in the codend ahead of the accumulating catch (Fig. 2; Eayrs et al., 1997). This allows escapement in the region of the codend where these species encounter the accumulating catch and turn to avoid it. However, the ineffectiveness of the BRDs used in the 2001 NPF spring fishing season (the current study) suggests that these devices were not used to maximise bycatch exclusion (e.g. installed away from their most effective position) or the behaviour of bycatch species restricted their ability to find a BRD opening and escape. The most commonly used BRD in 2001, the Bigeye BRD, was usually installed well ahead of the TED and the catch (Fig. 2d), which may be the most likely reason for poor reductions in small bycatch recorded in this study.

Results from other research suggest that the performance of BRDs in the NPF can be greatly improved. There is evidence from other studies that BRDs are capable of reducing catches of small bycatch, without significant prawn loss (Broadhurst, 2000; Steele et al., 2002; Courtney and Campbell, 2003a,b; Hall and Mainprize, 2005; Courtney et al., 2006). For example, a Square-mesh codend BRD (Brewer et al., 1997) has been trialled successfully in the NPF, reducing small bycatch by 33% without significant prawn loss. Although the impact of the NPF on the sustainability of these species is not known, it is likely that improved BRD performance will enhance the conservation status of the many species impacted in fished areas.

4.6. Commercially important prawns

Although TEDs and BRDs were introduced into the NPF to reduce the fishery's impact on bycatch species, the fishing industry is concerned about their effect on catches of commercially important prawns. The prawn losses measured here appear to be largely due to TEDs, but some loss due to the Bigeye BRD was also measured. Prawn loss through TEDs is most likely to result from either (i) poor construction, installation or tuning of the TED and/or BRD (Eayrs and Day, 2004a,b), (ii) blockages on the TED (usually by large animals), causing an unusually high number of animals to be diverted through the TED escape opening instead of passing back into the codend, or (iii) poorly functioning escape flap (discussed above).

The performance of TEDs or BRDs in other studies varies considerably (Broadhurst, 2000), influenced by the type of exclusion device, the bycatch composition, the catch volume, the availability of gear experts during the assessments, and the level of expertise in the industry. These studies also provide evidence that TEDs and BRDs can reduce bycatch with minimal or no loss of prawns. During the 2000 NPF spring fishing season, prawn catches were reduced by as little as 2.8% apparently due to an expert gear technologist tuning the devices (Day and Eayrs, 2001). There clearly is a potential for NPF fishers to reduce the 6% prawn loss we recorded by at least half as they become more familiar with the use and tuning of these devices.

Only two other studies have measured the change in the proportion of soft and damaged prawns in the commercial catch: Salini et al. (2000), during scientific trials of TEDs in Australia's NPF in 1995, measured reductions in soft and damaged prawns of between 6.1% and 34.7%; and Day and Eayrs (2001), in the same fishery in 2000, reported a 36.9% reduction in the proportion of soft and damaged prawns due to TEDs and BRDs. These studies demonstrate that the TED's removal of large animals (e.g. sea turtles, elasmobranchs and large sponges) from the codend can substantially improve the quality of prawns caught. Large animals can break and crush prawns when the catch accumulates in the codend, when the catch is compressed as the codend is lifted from the water and spilled onto the sorting tray, and when the large animals thrash around in the catch on the sorting tray. The reduction in soft and damaged prawns means that a greater proportion of the commercial catch has a higher market value.

4.7. Byproduct

The quantities of byproduct (mainly *T. indicus*, *T. orientalis*, *Teuthoidea* spp. or *A. pleuronectes*) caught in the NPF are small compared to the target catch of prawns. We found that TEDs or BRDs did not affect catches of these byproduct groups. Studies by Courtney and Campbell (2003a,b) in Queensland's prawn and scallop trawl fisheries are the only others to investigate the effect of TEDs or BRDs on the invertebrate byproduct species of a trawl fishery. In the deep water prawn trawl fishery Courtney and Campbell (2003a) found a small reduction in *Ibacus* sp. (Balmain bugs) in nets with a Wicks TED, no change in catches of *Ibacus* sp. in nets with Square-mesh codend BRDs, and no change in catches of *Sepia* spp. (cuttlefish species) in nets with different combinations of TEDs and BRDs. In the scallop trawl fishery Courtney and Campbell (2003b) found reductions of 20%, 21% and 28% in catches of legal sized (>75 mm CL) *Thenus* sp. (Moreton Bay bugs) when using square mesh codend BRDs, TEDs, and their combinations, respectively; and reductions of 71%, 10% and 78% in catches of undersized (<75 mm CL) *Thenus* sp. for the same gears.

4.8. Summary and conclusion

The introduction of TEDs and BRDs into the NPF has almost fully removed the fishery's impact on sea turtles and greatly reduced its impact on many of the highest risk sharks and rays. Their introduction (and of BRDs in particular) has not significantly reduced the catch of small animals. However, other studies (e.g. Brewer et al., 1997, 1998; Broadhurst, 2000; Broadhurst et al., 2002; Hall and Mainprize, 2005) have shown that impacts on sea snakes and small bycatch, in particular, can be reduced by improving the rigging and use of BRDs. More widespread uptake by other tropical fisheries, in particular, and improved use of these devices could contribute greatly to the conservation of demersal marine communities.

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