Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery

Ilona C. Stobutzki
Margaret J. Miller
Don S. Heales
David T. Brewer
CSIRO Marine Research
PO Box 120
Cleveland
Queensland 4163, Australia
E-mail address: ilona.stobutzki@.csiro.au

Abstract—The bycatch of Australia's northern prawn fishery (NPF) comprises 56 elasmobranch species (16 families). The impact of this fishery on the sustainability of these species has not been addressed. We obtained estimates of catch rates and the within-net survival of elasmobranchs. *Carcharhinus tilstoni, C. dussumieri, Rhynchobatus djiddensis,* and *Himantura toshi* represented 65% of the bycatch. For most species, >50% of individuals in the bycatch were immature, and some species recruited to the fishery at birth. For all species combined, 66% of individuals in the bycatch died in the trawl net.

The relative sustainability of elasmobranchs caught as bycatch was examined by ranking species with respect to their susceptibility to capture and mortality due to prawn trawling and with respect to their capacity to recover once the population was depleted. The species that were least likely to be sustainable were four species of pristids, *Dasyatis brevicaudata,* and *Himantura jenkinsii*. These are bottom-associated batoids that feed on benthic organisms and are highly susceptible to capture in prawn trawls. The recovery capacity of these species was also low according to our criteria. Our results provide a valuable first step towards ensuring the sustainability of elasmobranchs that are caught as bycatch by highlighting species for management and research. The effectiveness of turtle excluder devices (TEDs) in reducing elasmobranch bycatch varied greatly among species but was generally not very effective because most of the captured species were small.

Manuscript accepted 29 May 2002.
Fish. Bull. 100:800–821 (2002).

Worldwide, there is increasing concern over the capture of elasmobranchs (sharks and rays) as bycatch. The global landings of elasmobranchs are currently 760,000 metric tons (t) but a similar amount is part of unreported bycatch (Stevens et al., 2000). This bycatch is unmanaged in most fisheries and elasmobranchs are less able to sustain their populations under fishing regimes designed to sustain the target teleosts or invertebrates (Heuter, 1998). Some species have declined significantly because they are captured as bycatch, e.g. the common (*Dipturus batis*) and barndoor (*D. laevis*) skates (Brander, 1981; Casey and Myers, 1998). Despite these prevailing fishery practices, there have been few evaluations of the ability of elasmobranch species to sustain population levels (Walker and Hislop, 1998).

In general, an evaluation of the sustainability of any bycatch species is hampered by a lack of information. This is particularly so for elasmobranchs. Elasmobranch bycatch is often not recorded (Bonfil, 1994), or when it is recorded, the species composition is unknown. There is also limited biological information on most bycatch species, such as age at maturity, growth rate, and fecundity. This lack of information hampers the use of conventional stock assessment methods to determine the population status of these species.

Australia has a highly diverse elasmobranch fauna; almost half of the species are endemic (Last and Stevens, 1994). In northern Australian waters, elasmobranchs are impacted by a range of fisheries. Gillnet, longline, and dropline fisheries target shark species. Sharks, rays, and sawfish are also caught as bycatch in dropline and gillnet fisheries that target teleosts and in trawl fisheries that target teleosts or prawns. The current levels of elasmobranch bycatch are unknown for most of these fisheries. However, we know that the retained elasmobranch bycatch has increased because of the rising value of elasmobranch products, such as fins.

The largest fishery in northern Australia is the northern prawn fishery (NPF), which covers an area over 1,000,000 km^2 of ocean (Fig. 1) (McLoughlin et al., 1997). In the NPF, elasmobranchs contribute about 4% of the total bycatch weight (Stobutzki et al., 2001b). Prior to 2001, NPF trawlers were allowed to retain shark products but were restricted with respect to the amount on board at any one time. Management required fishermen to record retained bycatch in trawler logbooks, but the records were not validated. In 1999, 4177 kg of fillet, trunk, and whole shark and 1531 fins were recorded (Sharp et al.[1]). The compulsory use of turtle excluder devices (TEDs) in NPF trawls, beginning with the year 2000, have excluded some elasmobranchs from the bycatch (Brewer et al., 1998). However species-specific exclusion has not been examined.

[1] Sharp, A., J. Malcolm, and J. Bishop. 2000. Northern prawn fishery and Kimberley prawn fishery data summary 1999. Final report to Australian Fisheries Management Authority, Canberra, Australia. AFMA, PO Box 7051, Canberra BC ACT 2610, Australia.

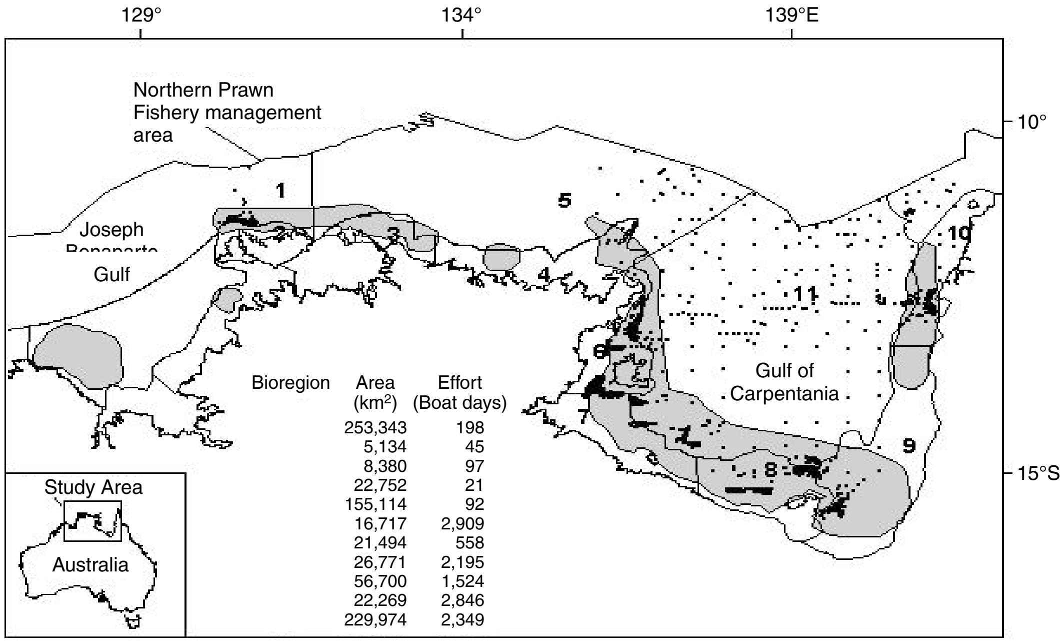

Figure 1

The management area of the northern prawn fishery (NPF) and the bioregions defined through the interim marine and coastal rationalization (IMCR) process (Thackway and Cresswell, 1998). The shaded area represents the regions fished by commercial prawn trawlers. The dots mark the positions of the trawls that were sampled to estimate the removal rates and total biomass of bycatch species (Table 1). The numbers refer to the bioregions (1=Oceanic Shoals, 2=Tiwi, 3=Cobourg, 4=Arnhem Wessel, 5= Arafura, 6=Groote, 7=Pellew, 8=Wellesley, 9=Karumba-Nassau, 10=West Cape York, 11=Carpentaria).

This study is one of several (Milton, 2001; Stobutzki et al., 2001a) that broadly examine the sustainability of bycatch species groups in the NPF. The aim of this study was to assess the relative sustainability of elasmobranch species taken as bycatch in the NPF. We use a broadbrush method developed by Stobutzki et al (2001a) to encompass the high diversity of and limited amount of information. This semiquantitative technique assesses the sustainability of species according to two overriding characteristics: 1) their susceptibility to capture and mortality due to trawling; and 2) the ability of a population to recover after depletion. Traditional population assessment methods have attempted to measure or model these factors. The broadbrush method uses biological and ecological criteria to rank species with respect to these two characteristics, maximizing the use of the limited information available. The method identifies species that are least likely to be sustainable in the bycatch, so that these can be the focus of further research and management.

Methods

Species present in the NPF and those captured as bycatch

A list of the elasmobranchs species recorded in the area of the NPF was compiled from Last and Stevens (1994). A list of species taken as NPF bycatch has been collated from two sources: 1) fishery research surveys undertaken within the NPF fishing grounds (Crocos and Coman, 1997; Stobutzki et al., 2001b; Blaber et al.[2]; Crocos et al.[3]); and 2) records of elasmobranch bycatch by observers on commercial vessels (these observers were either scientific staff or trained crew-members) (Stobutzki, 2001b; Pender et al.[4]; Stobutzki et al.[5]).

[2] Blaber, S., D. Brewer, C. Burridge, M. Farmer, D. Milton, J. Salini, Y-G. Wang, T. Wassenberg, C. Buxton, I. Cartwright, S. Eayrs, N. Rawlinson, R. Buckworth, N. Gill, J. MacCartie, R. Mounsey, and D. Ramm. 1997. Effects of trawl design on bycatch and benthos in prawn and finfish fisheries. Final report to Fisheries Research and Development Corporation (FRDC), Project 93/179, 190 p. FRDC, PO Box 222, Deakin West ACT 2600, Australia.

[3] Crocos, P. J., D. M. Smith, and G. Marsden. 1997. Factors affecting the reproductive performance of captive and wild broodstock prawns. Final report to the Fisheries Research and Development Corporation (FRDC), Project 92/51, 87 p. FRDC, PO Box 222, Deakin West ACT 2600, Australia.

[4] Pender, P. J., R. S. Willing, and D. C. Ramm. 1992. Northern prawn fishery bycatch study: distribution, abundance, size and use of bycatch from the mixed species fishery. Northern Territory Department of Primary Industry and Fisheries (NT DPIF), fishery report 26, 97 p. NT DPIF, GPO Box 3000, Darwin NT 0801, Australia.

[5] See next page for footnote 5.

Estimates of current bycatch rates and size frequency of species

Current bycatch rates were obtained from research and observer surveys. The research surveys and gear are described in detail in Stobutzki et al. (2001b) and Stobutzki et al.[5] Briefly, the research surveys sampled the nine major NPF fishing regions (1997 and 1998) to describe the bycatch. A scientific observer conducted three trips (of one-month duration) on commercial vessels in the NPF during 1996–97. A crew member of the commercial fleet was trained in elasmobranch identification and recorded the elasmobranch catch on commercial vessels during 1997. All elasmobranchs caught were identified, most to species, and their total number and weight were recorded. Where possible, each individual's sex, weight, and length were recorded. Total length (TL) was recorded for sharks, rhynchobatids, and pristids, and disc width (DW) was recorded for the remaining rays. Trawls during the research survey were of 0.5-h duration and a single trawl net was used. The observer data were collected from commercial trawls, 3–4 h in duration and where two nets were towed.

The overall catch rate for each species was calculated from the three sources. Catch rates were corrected for duration of the trawl and the length of the headrope. The catch rates of species in each trawl were converted into catch per swept area of the trawl as the numbers of individuals per square kilometer swept (no./km^2). We used the trawl speed recorded during the trawls and assumed that the prawn trawls had a spread of 0.66 of the headrope length (Bishop and Sterling, 1999). Individuals of the species *Carcharhinus tilstoni* and *C. limbatus* are difficult to distinguish. Genetic studies in this region have indicated that *C. limbatus* is very rare (Lavery and Shaklee, 1991); therefore all specimens were recorded as *C. tilstoni*.

Size at first maturity and fecundity

Because there is limited biological information on dasyatidids and gymnurids (Last and Stevens, 1994), we retained specimens from the scientific surveys to obtain preliminary estimates of size at maturity and fecundity. For females, gonad weight, diameter of the largest ovum in the ovary, and their fecundity status (whether they were pregnant of not, and whether there were *in utero* embryos present) were recorded. For pregnant individuals, the number of embryos was recorded. For males, we recorded gonad weight, clasper length, and the calcification state of the clasper (uncalcified, partially calcified, or totally calcified). Size at sexual maturity for females was estimated as the length of the smallest pregnant individual; for males it was determined from clasper size and calcification (Bass et al., 1973).

Within-net survival

Currently there is no information on the survival rate of elasmobranchs caught as bycatch in prawn trawlers. The October 1998 research survey and crew-member observer (Table 1) recorded whether individuals were dead or alive when landed on the deck. This record provided an estimate of the within-net mortality, which was no doubt lower than the total mortality because some individuals recorded as alive would subsequently die as a result of capture. Logistic regressions (PROC LOGISTIC, SAS 1997) were used to determine whether there was a relationship between the likelihood of survival and the length or sex of an individual. The species were analyzed in two groups: sharks (species where TL was recorded) and rays (species where DW was recorded).

Assessment of the sustainability of elasmobranch species

The assessment was based on the method developed by Stobutzki et al. (2001a) which was designed to accommodate a high diversity of and a limited amount of information. The sustainability of the species was assumed to be dependent on two overriding features: 1) the susceptibility of the species to capture and mortality caused by trawling and 2) the capacity of the population to recover after depletion. Biological and ecological information was collated from the literature (Compagno, 1984a; 1984b; Last and Stevens, 1994; Froese and Pauly[6]). This information was used to rank the species along two axes describing the overriding features:

Axis 1: The susceptibility of a species to capture and mortality due to a prawn trawl (susceptibility),

Axis 2: The capacity of a species to recover once the population is depleted (recovery).

Each feature (or axis) was derived from several criteria (listed below) that summarized aspects of the biology of the species (six criteria for axis 1 and five criteria for axis 2). Each species was given a ranking from 1 to 3 for each criterion (the definitions of the ranks for the criteria are provided in Table 2). A rank of 1 suggested that the species was highly susceptible to capture or had little capacity to recover; a rank of 3 suggested that the species had a low susceptibility to capture or a high capacity to recover. Depending on the criterion, these ranks were based on categorical or continuous data (Table 2). Where continuous data were used, because no information was available to assign divisions between the ranks, the range of the data was divided into thirds to create the categories.

[5] Stobutzki, I., S. Blaber, D. Brewer, G. Fry, D. Heales, P. Jones, M. Miller, D. Milton, J. Salini, T. Van der Velde, Y-G. Wang, T. Wassenberg, M. Dredge, A. Courtney, K. Chilcott, and S. Eayrs. 2000. Ecological sustainability of bycatch and biodiversity in prawn trawl fisheries. Final report to the Fisheries Research and Development Corporation (FRDC), Project 96/257, 512 p. FRDC, PO Box 222, Deakin West ACT 2600, Australia.

[6] Froese, R., and D. Pauly, eds. 1999. Fishbase 99. URL htpp://www.fishbase.org. [Date accessed: November 1999.]

Table 1

The surveys that contributed to the estimate of the removal rate (*), total biomass, and within-net survival for elasmobranch species in the Northern Prawn Fishery, Australia. # indicates the surveys whose data contributed to the list of bycatch species.

Year	Month	Type	Gear	No. of trawls	No of nets used	Reference
1998*#	Sep–Oct	research survey	Florida flyer	366	1	Stobutzki et al.[5]
1997*#	Oct	research survey	Florida flyer	424	1	Stobutzki et al. (2001b)
1997*#	Sep–Oct	scientific observer	Florida flyer	60	2	Stobutzki et al. (2001b)
1997*#	Aug–Oct	crew member observer	Florida flyer	141	2	Stobutzki et al.[5]
1997*#	May–Jun	scientific observer	Florida flyer	76	2	Stobutzki et al. (2001b)
1997*#	Feb–Mar	research survey	Florida flyer, Engels	248	1	Stobutzki et al. (2001b)
1996*#	Sep	scientific observer	Florida flyer	83	2	Stobutzki et al. (2001b)
1995#	Jun	research survey	Florida flyer	38	1	Blaber et al.[2]
1995#	Oct–Nov	research survey	Florida flyer	39	1	Blaber et al.[2]
1995#	Feb–Mar	research survey	Florida Flyer	39	1	Blaber et al.[2]
1994#	Nov	research survey	Florida flyer	7	2	Crocos and Coman (1997); Crocos et al.[3]
1994#	Jul	research survey	Florida flyer	7	2	Crocos and Coman (1997); Crocos et al.[3]
1994#	Ma	research survey	Florida flyer	4	2	Crocos and Coman (1997); Crocos et al.[3]
1994#	Mar	research survey	Florida flyer	5	2	Crocos and Coman 1997; Crocos et al.[3]
1993#	Nov	research survey	Florida flyer	81	1	Crocos and Coman 1997; Crocos et al.[3]
1993#	Oct	research survey	Florida Flyer	5	2	Blaber et al.[2]
1993#	Aug	research survey	Florida Flyer	9	2	Crocos and Coman (1997; Crocos et al.[3]
1993	Jan–Feb	research survey	Engels, Frank and Bryce	71	1	Milton et al. (1995)
1991	Nov	research survey	Frank and Bryce	62	1	Milton et al. (1995)
1990	Nov–Dec	research survey	Frank and Bryce	128	1	Blaber et al. (1994); Milton et al. (1995)

Where species-specific information was not available, a species was given the same rank as other species within its family for the criteria water column position, diet, and day and night catchability. For the other criteria, where it was not necessarily logical that family members would be similar, or where family information was not available, a rank of 1 was assigned as a precautionary approach.

Axis 1: Susceptibility of a species to capture and mortality induced by the prawn trawl

There were six criteria (water column position, survival, range, day and night catchability, diet, and depth range) on axis 1.

Water column position Because prawn trawls fish close to the sea floor, demersal species are more likely to be captured than pelagic species.

Survival This estimate was based on the survival-in-the-net data outlined previously. The possible survival range of 0–100% was divided into thirds for the divisions between the ranks.

Range This criterion reflects the geographic spread of a species within the NPF and was determined from the research, scientific, and crew-member observer surveys undertaken by Stobutzki et al.[5] and Stobutzki et al. (2001b). Commercial fishing is highly aggregated within the managed area of the fishery. The nine regions of highest effort were surveyed in 1997 (Table 1) and the presence or absence of each species was recorded in each region. We assumed that species with a restricted range could be impacted more heavily by trawling than those with a broader range.

Day and night catchability The tiger prawn fishery is predominantly a nighttime fishery (McLoughlin et al., 1997). Species with a higher catchability at night are more susceptible to capture as bycatch. The relative catch rate of species during night and daytime trawling was compared during research surveys in October 1997 (Table 1).

Diet This criterion reflects whether the diet of the species may attract them to trawl grounds and whether they feed within the area of the water column swept by a prawn trawl. Species that feed on commercial prawns may be attracted to the commercial fishing grounds, increasing their susceptibility to capture. Species that feed on demersal organisms are assumed to be more susceptible to prawn trawls than species that feed higher in the water column.

Depth range Commercial trawls in the NPF are made mainly between 15 m and 40 m (Somers, 1994). An overlap between the depth range of trawling and the preferred

Table 2

The criteria used to assess 1) the relative susceptibility of bycatch species to capture and mortality due to prawn trawls and 2) their recovery capacity after depletion due to trawling. These combine to provide the ranks for the axes in Figure 2. For each criterion the definition of the three ranks is given, as well as the weighting score and the percentage of species for which species-specific information was used to rank them.

Criteria	Weight	Species-specific information (%)	Rank 1	Rank 2	Rank 3
Susceptibility					
Water column position	3	100	Demersal or benthic	Not applicable	Benthopelagic or pelagic
Survival	3	18	Probability of survival <33%	Probability of survival between 33% and 66%, inclusive	Probability of survival >66%
Range	2	71	Species range ≤3 fishery regions	3 fishery regions < species range ≤6 fishery regions	Species range >6 fishery regions
Day and night catchability	2	32	Higher catch rate at night	No difference between night and day	Higher catch rate at day
Diet	2	55	Known to, or capable of, feeding on commercial prawns or benthic organisms	Not applicable	Feed on pelagic organisms
Depth range	1	100	Less than 60 m	Not applicable	Deeper than 60 m
Recovery					
Probability of breeding	3	42	Probability of breeding before capture <50%	Probability of breeding before capture not significantly different from 50%	Probability of breeding before capture >50%
Maximum size	3	100	Maximum disc width >1755 mm	853 mm < maximum disc width ≤1755 mm	Maximum disc width ≤853 mm
			Maximum total length >4781 mm	1861 mm < maximum total length ≤4781 mm	Maximum total length ≤1861 mm
Removal rate	3	79	Removal rate >66%	33% < removal rate ≤66%	33% ≤ removal rate
Annual fecundity	1	52	Annual fecundity ≤5 young per year	5 young per year < annual fecundity ≤19 young per year	Annual fecundity >19 young per year
Mortality index	1	64	mortality index >3.47	0.92 < mortality index ≤3.47	mortality index ≤0.92

depth range of species will influence their susceptibility to capture: a higher proportion of a species' population is likely to be taken if there is an overlap. Species with a broader depth range may have a spatial refuge from trawling, making them less susceptible. The depth range of species was determined from previous research surveys in the NPF and from the literature.

Axis 2: The capacity of a species to recover once the population is depleted

There were five criteria (probability of breeding, maximum size, removal rate, annual fecundity, mortality index) on this axis.

Probability of breeding We assumed that a species is likely to have a greater capacity to recover from a decrease in population due to trawling if most individuals are captured after they have bred. The probability that an individual of a species had bred before capture was determined from the mean length at capture in relation to the species' recorded size at maturity. The mean length at capture of a species was recorded in the research and observer surveys 1996–98 (Table 1). Size at maturity was determined from the available literature and from our estimates outlined previously.

A *t*-test (Sokal and Rohlf, 1996) was used to determine whether the mean length at capture was significantly different from the size at maturity for each species.

Table 3

The elasmobranch species that are known to occur in the region of the northern prawn fishery (NPF), Australia, and of these species, those that have been recorded in NPF bycatch (Table 1). The labels in parentheses refer to the species abbreviations in Figure 2.

Family	Recorded in bycatch: Yes		No
Carcharhinidae	*Carcharhinus albimarginatus*	(Cal)	*Carcharhinus amblyrhynchoides*
	Carcharhinus amboinensis	(Cam)	*Carcharhinus amblyrhynchos*
	Carcharhinus brevipinna	(Cb)	*Carcharhinus cautus*
	Carcharhinus dussumieri	(Cd)	*Carcharhinus obscurus*
	Carcharhinus fitztroyensis	(Cf)	*Carcharhinus plumbeus*
	Carcharhinus leucas	(Cle)	*Carcharias taurus*
	Carcharhinus limbatus	(Cli)	*Carcharinus falciformis*
	Carcharhinus macloti	(Cm)	*Carcharinus melanopterus*
	Carcharhinus sorrah	(Cs)	*Loxodon macrorhinus*
	Carcharhinus tilstoni	(Ct)	*Rhizoprionodon oligolinx*
	Galeocerdo cuvier	(Gc)	*Triaenodon obesus*
	Negaprion acutidens	(Na)	
	Prionace glauca	(Pg)	
	Rhizoprionodon acutus	(Rac)	
	Rhizoprionodon taylori	(Rta)	
Dasyatidae	*Amphotistius annotata*	(Aa)	*Dasyatis fluviorum*
	Dasyatis brevicaudatus	(Db)	*Taeniura lymma*
	Dasyatis leylandi	(Dl)	
	Dasyatis kuhlii	(Dk)	
	Dasyatis sp. A	(Dsa)	
	Dasyatis thetidis	(Dt)	
	Himantura fai	(Hf)	
	Himantura granulata	(Hg)	
	Himantura jenkinsii	(Hj)	
	Himantura sp. A	(Hsa)	
	Himantura toshi	(Ht)	
	Himantura uarnak	(Hua)	
	Himantura undulata	(Hun)	

continued

Maximum size The maximum size of a species was used as an indicator of the species' relative recovery rate. In general, larger species tend to live longer and their populations recover more slowly (Roberts and Hawkins, 1999). Size appears to be a good predictor of vulnerability for marine fishes (Jennings et al., 1999), and in particular skates (Walker and Hislop, 1998; Dulvy et al., 2000). Estimates of maximum size came from the literature. Species were grouped according to whether DW or TL was measured. The range of the maximum sizes of species was calculated and divided into thirds for the divisions between the ranks.

Removal rate We assumed that species with a higher proportion of their biomass removed as bycatch would have a lower capacity to recover. The estimate of removal rate was based on the catch rates from research surveys and scientific observer collections undertaken between 1996 and 1998 (Table 1). We assumed that these catch rates were representative of the overall catch rates in the commercial fishery.

The catch rates of bycatch species vary spatially within the NPF (Stobutzki et al., 2001b). Therefore, the fishery was stratified before we estimated the mean catch rate, using the bioregions identified in the Interim Marine and Coastal Regionalization for Australia (IMCRA) process (Thackway and Cresswell, 1998) (Fig. 1). A mean catch rate for each species was calculated for each bioregion where commercial tiger prawn trawling occurs.

The biomass (in numbers of individuals per year) of bycatch removed by the commercial fishery was estimated by multiplying the mean catch rate calculated above by the 1997 commercial tiger prawn fishery effort in each bioregion (Table 3). Commercial fishing effort is recorded in log books in boat days (held by the Australian Fisheries Management Authority). One boat day was assumed to be the

Table 3 (continued)

Family	Recorded in bycatch		
	Yes		No
Dasyatidae (continued)	*Pastinachus sephen*	(Ps)	
	Taeniura meyeni	(Tm)	
	Urogymnus asperrimus	(Ua)	
Ginglymostomatidae	*Nebrius ferrugineus*	(Nf)	
Gymnuridae	*Gymnura australis*	(Ga)	
Hemigaleidae	*Hemigaleus microstoma*	(Hm)	*Hemiscyllium ocellatum*
	Hemipristis elongatus	(He)	*Hemiscyllium trispeculare*
Hemiscylliidae	*Chiloscyllium punctatum*	(Cp)	
Mobulidae			*Manta birostris*
			Mobula eregoodootenkee
Myliobatidae	*Aetobatus narinari*	(Ana)	
	Aetomylaeus vespertilio	(Av)	
	Aetomyleus nichofii	(Ani)	
Narcinidae	*Narcine westraliensis*	(Nw)	*Narcine* sp. A
Orectolobidae	*Orectolobus ornatus*	(Oo)	*Eucrossorhinus dasypogon*
			Orectolobus wardi
Pristidae	Anoxypristis cuspidata	(Ac)	
	Pristis clavata	(Pc)	
	Pristis microdon	(Pm)	
	Pristis pectinata	(Pp)	
	Pristis zijsron	(Pz)	
Scyliorhinidae	*Atelomycterus fasciatus*	(Af)	*Atelomycterus macleayi*
	Galeus sp. A	(Gsa)	
Sphyrnidae	*Eusphyra blochii*	(Eb)	
	Sphyrna lewini	(Sl)	
	Sphyrna mokarran	(Sm)	
Squatinidae	*Squatina* sp. A	(Ssa)	
Stegostomatidae	*Stegostoma fasciatum*	(Sf)	
Rhincodontidae			*Rhiniodon typus*
Rhinobatidae	*Rhinobatos typus*	(Rty)	*Aptychotrema* sp. A
Rhynchobatidae	*Rhynchobatus djiddensis*	(Rd)	
	Rhina ancylostoma	(Ran)	

equivalent of 14 hours of trawling with two nets and with 14-fathom (25.48 m) headropes at a speed of 3.2 knots (5.9 km/h) (Bishop and Sterling, 1999).

The estimate of the total amount removed for a species within the whole fishery was calculated by summing the removal estimates for the bioregions. This estimate was then converted to a proportion of the estimated total biomass of the species.

An estimate of the total biomass of each species in the bioregions where tiger prawn trawling occurs was generated from all research and scientific observer surveys conducted in the NPF during the 1990s (Fig. 1, Table 1). The gears used were prawn trawls (Florida flyer nets) and two types of fish trawls (Frank and Bryce trawls and Engel trawls). Both night and daytime trawling were undertaken. Both prawn-trawl and fish-trawl surveys were analyzed in order to cover the management area of the fishery.

The catch rates of species in each trawl were converted to the catch per swept area of the trawl as described previously. The fish trawls were assumed to have a spread of 0.6 of the headrope length (Blaber et al., 1994). A mean catch rate for each gear at each time (day or night) was calculated in each bioregion, resulting in up to six catch rate estimates for a species in a bioregion. The highest of these means was used for each species in that bioregion. This catch rate was then multiplied by the area of the bioregion to give an estimate of total numbers of individuals in the bioregion. Currently there are no robust estimates of the catchability coefficients for the various trawl gears and therefore a catchability coefficient of one was assumed for all species. Such a high catchability coefficient is unlikely to be valid for most species and results in an underestimate of the total biomass. For the two bioregions where commercial tiger prawn trawlers operate, there was no survey data from which to estimate catch rates (bioregions 4 and 5, Fig. 1). Therefore, the mean catch rate of the other bioregions was used to allow an estimate of catch rate. The total biomass of each species was calculated by summing the estimates for the bioregions. The removal rate would range between 0% and 100%; this range was divided into thirds for the division between the ranks.

Annual fecundity The annual fecundity of species was estimated from data in the literature and the biological samples collected during our study. The annual fecundity of a species was estimated as the average number of pups per female multiplied by the number of times the females bred per year. Where the frequency of breeding was not known, it was assumed to be annual, unless the known gestation period was longer than 12 months. The range of fecundities was calculated and divided into thirds for the divisions between the ranks.

Mortality index The recovery capacity of a population is likely to be related to its fishing mortality rate (Sparre and Venema, 1992). A measure of this rate can be derived from the length-frequency of a species and the von Bertlanffy growth parameters (Sparre and Venema, 1992). However, for most species von Bertalanffy parameters were not available and therefore an index of mortality was calculated as follows:

$$\textit{Mortality index} = (L_{max} - L_{ave})/(L_{ave} - L_{min}), \qquad (1)$$

where L_{max} = the maximum length;
L_{ave} = the mean length at capture in the fishery; and
L_{min} = the smallest length caught.

The closer the mean length of captured individuals (L_{ave}) to the maximum length (L_{max}) the lower the mortality the population is subject to. As mortality due to fishing increases, the mean length of species in a population approaches the minimum length (L_{min}). For our analysis, we assumed constant catchability and mortality across the whole length range caught. The L_{ave} and L_{min} were calculated from length data collected during our study.

The range of mortality estimates was calculated and divided into thirds for the divisions between the ranks.

Analysis of criteria

Partial correlations (Sokal and Rohlf, 1996) were used to determine whether there was any redundancy in the criteria. Strong correlations would suggest that two or more criteria explained the same factors, which would lead to overemphasis of their effect. One of the correlated criteria was, therefore, removed.

The total susceptibility, or removal ranking, of a species was determined by the following equation:

$$S_i = \frac{\sum_{j=1}^{n} w_j R_i}{\sum_{j=1}^{n} w_j}, \qquad (2)$$

where S_i = the total susceptibility or recovery ranks for species i;
w_j = the weighting for criterion j;
R_i = the rank of species i for criterion j; and
n = the number of criteria on each axes.

The criteria were weighted to reflect the relative importance of each criterion in determining the overall characteristic and the robustness and quality of the data (Table 2), the latter in terms of the amount of species-specific information and the scale of the information available. The criteria that were seen as major determinants of susceptibility or recovery and for which there were more robust data were weighted highest. This weighting was done in collaboration with the NPF Fishery Assessment Group.

The total susceptibility and recovery ranks for the species were graphed to determine the relative sustainability of the species caught as bycatch by prawn trawlers. The species least likely to be sustainable would be identified as the species with the lowest ranks on both axes.

Contour lines were drawn on the graph to group species that would be similar with respect to their sustainablity. Because neither susceptibility, nor recovery alone, provide a complete index to the sustainability of species, the index is a combination of these two features. Recovery is likely to be conditionally important on susceptibility, and therefore, a multiplicative relationship between the two axes is appropriate. We assumed that this relationship is symmetrical and given this assumption, the contour lines followed the equation

$$16(y - 0.75)\,(x - 0.75) = 4, 9, 16, 25, 36, 49. \qquad (3)$$

The impact of turtle excluder devices on elasmobranch bycatch

Data on the size of species captured in nets fitted with TEDs and with nets with standard codends were available from two sources. The crew-member observer recorded seven pairs of trawls in which one net was fitted with a TED and one had a standard codend. The TED was a Seymour TED with 110-mm bar spacing. Previous research surveys from one area of the NPF also recorded information on elasmobranchs captured in nets with and without TEDs. The TEDs were AusTEDs, NørdMore Grids, and SuperShooters; the design of these nets is detailed in Brewer et al. (1998).

The length frequency of elasmobranchs caught in nets with TEDs was compared to the length frequency of elasmobranchs caught in nets without a TED. First, species were grouped into sharks (TL measured) and rays (DW measured) for analysis. The mean length of individuals captured in nets fitted with a TED was compared with that of elasmobranchs caught in nets with a standard codend by using a one-way ANOVA. The lengths were transformed (log (*length* + 1)) prior to analysis to normalize the data. There were sufficient data for three species of shark *(Rhizoprionodon acutus, Hemigaleus microstoma,* and *Carcharhinus dussumieri*), two stingrays (*Dasyatis leylandi* and *Himantura toshi*) and a shovel-nosed ray (*Rhynchobatus djiddensis)* to examine them separately with one-way ANOVAs.

Results

Species captured as bycatch in prawn trawls of the NPF

At least 79 species of elasmobranchs from 18 families, inhabit the NPF region (Table 3). Of these, 56 species (16 families) have been recorded in the prawn-trawl fishery bycatch (Table 3). The Carcharhinidae and Dasyatidae, the most species-rich families in the region, are the also the families for which the highest number of species are recorded in bycatch (Table 3). There are 9 families in which all species found in this region have been recorded in bycatch (Table 3).

Current catch rates

In the research and observer surveys (1996 and 1998) 44 species of elasmobranchs were recorded. The highest overall catch rates were for *Carcharhinus tilstoni, C. dussumieri, R. djiddensis,* and *H. toshi* (Table 4). These four species contributed almost 65% of the observed elasmobranch bycatch. *Carcharhinus dussumieri* and *C. tilstoni* were recorded in 20% of all trawls, *R. dijiddensis* in 14%, and *H. toshi* in 17%.

Size at first maturity and fecundity

Specimens of five species of ray were examined to assess size at first maturity and to provide estimates of fecundity (Table 5). None of the species showed a change in gonadosomatic index (GSI) or diameter of the largest egg, both of which would clearly indicate maturity. The average number of embryos was low (Table 5); most species had one or two, with the exception of *Gymnurus australis,* which had up to five embryos present.

Males of most species showed an increase in GSI with calcification of the claspers. The estimates of size at maturity for the males were lower than the estimates for females for four of the five species (Table 5). However, this finding might have been influenced by the low numbers of pregnant females sampled (Table 5). The size at maturity of the males appeared to be between 44% and 79% of the maximum size for the species.

The mean size of rays caught in bycatch ranged from 182 mm for *D. leylandi* to 1117 mm for *H. toshi* (Table 6). The mean size of sharks ranged from 541 mm for *Carcharhinus sorrah* to 1643 mm for *Rhina ancylostoma* (Table 6). For 30 species, a size at birth was available from the literature and, of these, eight species were caught in bycatch at this size (Table 6).

Where an estimate of the size at first maturity (L_m) was available for a species, an estimate could be made of the percentage of individuals captured that were mature. In species with sufficient samples sizes, the percentage of mature individuals caught ranged from <1% for *S. lewini,* to 54% for *R. acutus* (Table 6). Species such as *D. leylandi* had an average size at capture not significantly different from L_m, indicating that, on average, half the individuals caught had reached maturity before capture. Species such as *R. acutus*, with an average size less than L_m, were those for which the majority were unlikely to have bred before capture. At the other extreme were species such as *G. australis*, for which it was likely that the majority had reached maturity before capture (Table 6).

The female-to-male ratio of individuals caught was close to 1:1 for the two common species*, D. leylandi* and *C. dussumieri* (Table 6). However, other species had a range from predominantly male (e.g. *R. acutus*) to predominantly female (e.g. *H. toshi*) (Table 6).

Within-net survival

Whether an individual was alive or dead when landed on the deck was recorded for 847 animals. Overall 56% were dead after capture in the trawl and 44% were alive. Both sharks and rays showed that the probability of survival was lower for males than for females (sharks χ^2=19.7, P<0.001, rays χ^2=10.5, P=0.0012) and that survival increased with length of the individual (sharks χ^2=4.8, P=0.029, rays χ^2=11.08, P=0.0009). Two-thirds of male sharks and rays were recorded as dead after capture in the trawl (Table 7). The mean size of rays and sharks that died (sharks 684 (±10 SE) mm, rays 424 (±41 SE) mm) was smaller than the mean size of those that survived (sharks 797 (±17 SE) mm, rays 546 (±33 SE) mm). The overall percentage of individuals of a species that died varied from 10% *(R. djiddensis*) to 82% (*C. dussumieri* and *R. acutus*) (Table 7).

Assessment of the sustainability of elasmobranch species

The 56 species of elasmobranchs recorded as bycatch in the NPF were ranked on each of the criteria on the two axes (Appendices 1 and 2). The extent to which species-specific information was available varied among the criteria (Table 2). Water column position, depth range, and maximum size had species-specific information for all species. Survival and day and night catchability had little species-specific information.

Most of the criteria were not correlated (Table 8). On the susceptibility axis the strongest correlation was between diet and water column position (Table 8). However, both criteria were retained because we believed there was sufficient difference between them; the correlation coefficient (r) was only 0.67. On the recovery axis no correlations were significant (Table 8).

On the susceptibility axis (Appendix 1) the four species of Pristidae, *Atelomycterus fasciatus, Himantura jenkinsi,* and *Stegostoma fasciatum* had a rank of 1, the lowest possible rank, suggesting they were the most susceptible to capture

Table 4

The percentage of trawls in which species were caught, mean catch rate (SE=standard error), and the percentage of catch contributed by each species.

Family	Species	No./km^2			
		% of trawls	Mean	SE	% of catch
Carcharhinidae	*Carcharhinus albimarginatus*	0.10	0.58	0.41	0.26
	Carcharhinus amboinensis	0.20	0.04	0.04	0.02
	Carcharhinus dussumieri	20.57	38.80	4.89	17.54
	Carcharhinus fitztroyensis	0.20	0.80	0.40	0.35
	Carcharhinus macloti	0.20	0.98	0.50	0.43
	Carcharhinus sorrah	1.67	1.47	0.57	0.65
	Carcharhinus tilstoni	19.49	44.20	5.98	20.07
	Galeocerdo cuvier	0.20	0.01	0.00	<0.01
	Negaprion acutides	0.10	0.00	0.00	<0.01
	Rhizoprionodon acutus	9.15	10.61	1.63	4.83
	Rhizoprionodon taylori	0.10	0.00	0.00	<0.01
Dasyatidae	*Amphotistius annotata*	1.97	1.56	0.41	0.74
	Dasyatis kuhlii	2.56	1.48	0.56	0.69
	Dasyatis leylandi	15.35	9.44	1.18	4.48
	Dasyatis sp. A	0.10	0.00	0.00	<0.01
	Dasyatis thetidis	0.49	0.03	0.01	0.01
	Himantura fai	0.10	0.01	0.00	<0.01
	Himantura granulata	0.20	0.01	0.01	<0.01
	Himantura jenkinsii	0.59	2.11	0.77	0.95
	Himantura sp. A	2.17	0.11	0.04	0.05
	Himantura toshi	17.72	27.85	3.10	12.84
	Himantura uarnak	0.98	1.44	0.58	0.70
	Himantura undulata	0.89	0.96	0.40	0.43
	Pastinachus sephen	3.44	0.69	0.31	0.31
	Taeniura meyeni	0.10	0.40	0.28	0.18
	Urogymnus asperrimus	0.39	0.40	0.28	0.18
Ginglymostomatidae	*Nebrius ferrugineus*	0.10	0.58	0.41	0.26
Gymnuridae	*Gymnura australis*	5.91	8.02	1.64	3.82
Hemiscylliidae	*Chiloscyllium punctatum*	5.41	11.83	1.96	5.42
	Hemigaleus microstoma	9.84	9.64	1.55	4.56
	Hemipristis elongatus	0.20	0.02	0.02	0.01
Myliobatidae	*Aetobatus narinari*	0.30	0.60	0.41	0.27
	Aetomylaeus nichofii	1.08	1.57	0.61	0.74
Orectolobidae	*Orectolobus ornatus*	0.10	0.52	0.52	0.27
Pristidae	*Anoxypristis cuspidata*	0.98	0.71	0.42	0.32
	Pristis zijsron	0.10	0.02	0.02	0.01
Rhinobatidae	*Rhinobatos typus*	0.39	0.02	0.01	0.01
Rhynchobatidae	*Rhina ancylostoma*	0.89	0.10	0.04	0.05
	Rhynchobatus djiddensis	14.27	30.87	3.39	14.26
Scyliorhinidae	*Atelomycterus fasciatus*	0.49	0.18	0.08	0.08
Sphyrnidae	*Eusphyra blochii*	0.20	0.04	0.04	0.02
	Sphyrna lewini	2.95	6.91	1.52	3.07
	Sphyrna mokarran	0.39	0.02	0.02	0.01
Stegostomatidae	*Stegostoma fasciatum*	2.17	2.17	1.02	1.10

Table 5
The estimated size (disc width) at first maturity and mean number of pups for ray species (sample size is shown in parentheses; SE=standard error).

	Size at maturity (mm)				Number of pups		
Species	Male		Female		Mean	SE	
Amphotistius annotata	200	(9)	233	(8)	1.5	0.7	(2)
Dasyatis kuhlii	300	(10)	378	(6)	2	—	(1)
Dasyatis leylandi	185	(103)	180	(110)	1.1	0.3	(17)
Gymnura australis	350	(29)	610	(16)	3.2	1.2	(6)
Himantura toshi	400	(31)	660	(21)	1.5	0.7	(2)

and mortality. The next 19 species had a rank of 1.15, also low. *Carcharhinus tilstoni, C. macloti, Sphyrna lewini, Prionace glauca, C. brevipinna,* and *Aetomyleus nichofii* had the highest ranks on this axis (>1.92), indicating that they were the least susceptible to capture and mortality.

On the recovery axis (Appendix 2) *Aetomyleus vespertilio, Dasyatis brevicaudatus, Pristis clavate,* and *P. pectinata* had the lowest ranks, indicating that they had the lowest capacity to recover. *Gymnura australis, H. toshi, Hemigaleus microstoma,* and *R. taylori* had the highest ranks on this axis and therefore the highest capacity to recover.

When the ranks of the species on the two axes were plotted (Fig. 2), *Dasyatis brevicaudatus, P. pectina, P. clavata, P. microdon, P. zijsron,* and *Himantura jenkinsii* ranked the lowest on the combination of the two axes, indicating that they were the least likely to be able to survive capture as bycatch. The species *Eusphyrna blochii, H. toshi, C. macloti,* and *C. tilstoni* ranked the highest on the two axes, indicating that they were the most likely to be able to survive capture as bycatch.

The impact of turtle exclusion devices on elasmobranch bycatch

Both sharks and rays taken as bycatch were significantly smaller in nets with a codend fitted with a TED (Table 9). The length frequency of the sharks and rays caught in the nets with TEDs showed a lower proportion of the larger individuals (Fig. 3). Where individual species were examined, there was a decrease in the size of *C. dussumieri* and *R. djiddensis* caught in the net with a TED (Table 9). There was no significant difference in size for *H. microstoma, A. annotata,* and *H. toshi* (Table 9). However, significantly larger individuals of *Rhizoprionodon acutus* were caught in the net with a TED (Table 9).

Discussion

Of the elasmobranch species known to inhabit this region, 71% were taken as bycatch in the NPF. The highly diverse bycatch is characteristic of tropical prawn trawl fisheries (Hall, 1999). Two critical pieces of information for assessing the impact of trawling in this region on elasmobranchs are the catch rates and survival of species.

Current catch rates

Although the bycatch was highly diverse, four species dominated the catch of the present study (*C. tilstoni, C. dussumieri, R. djiddensis,* and *H. toshi,* Table 4), occurring in 14–20% of trawls, so that one individual was seen at least every seven trawls. However, most species (75%) contributed <1% of the catch and had low catch rates (Table 4). However, even low catch rates can result in a large overall take of individuals. The fishery recorded 18,314 days of fishing in 1999 (Sharp et al.[1]) and if each day consisted of four trawls (Bishop and Sterling, 1999), 73,256 trawls (with two nets) would have been undertaken in the year. Hence for a species occurring in 1% of trawls, 733 individuals would have been caught in the year.

There are no long-term catch data available that can be examined for changes in catch rates of elasmobranch species. Although shark byproducts are recorded in NPF logbooks, the data are of limited value because they are not validated and not species-specific. Pender et al.[4] surveyed the bycatch in Northern Territory waters of the NPF during the 1980s. Rhynchobatids (71% of the elasmobranch catch), carcharhinids (12%) and dasyatids (11%) dominated the catch (Pender et al.[4]). All species recorded by Pender et al.[4] were recorded in our study. Direct comparisons of the catch rates of Pender et al.[4] with those of our study were not possible because of differences in gear, season, and region.

Most elasmobranchs caught in bycatch are small (<1000 mm). For some species, this means that most individuals have not bred before capture (Table 6) and therefore the fishery will have a greater adverse impact on the species. At least eight species were caught at sizes close to their known birth size (Table 6). This finding suggests that pupping may occur in the area of the fishery. Whether these species have restricted pupping grounds is unknown.

Within-net survival

Our estimates of within-net survival are the first for elasmobranchs in prawn trawls. The results suggest that most

Table 6

The mean, minimum (min), and maximum (max) size (TL or DW) of elasmobranch species caught in nighttime prawn trawling. The size at maturity (L_m) and at birth (pup size) are shown based on Last and Stevens (1994) or Table 5. The percentage of individuals caught that were mature (% mature) and the sex ratio are also shown. SE = standard error; n = sample size; P is the probability that the mean length at capture is different from L_m.

		Size (mm)					Sex ratio					Pup
Family	Species	Mean	SE	Min.	Max.	n	F:M	n	L_m	P	% mature	size (mm)
Carcharhinidae	*Carcharhinus albimarginatus*	850	—	—	—	1	—	—	1700	—	100	550
	Carcharhinus amboinensis	1700	—	—	—	1	—	—	2100	—	0	600
	Carcharhinus dussumieri	636	6	270	850	377	1.08	139	700	<0.001	41	350
	Carcharhinus fitzroyensis	1045	225	820	1270	2	—	—	800	>0.5	50	500
	Carcharhinus macloti	745	75	670	820	2	—	—	690	>0.5	20	450
	Carcharhinus sorrah	542	43	300	950	25	3.03	16	900	<0.001	8	500
	Carcharhinus tilstoni	794.3	9	100	1950	344	0.95	84	1200	<0.001	0.6	600
	Galeocerdo cuvier	1175	285	890	1460	2	all M	1	3000	>0.1	0	500
	Negaprion acutidens	2600	—	—	—	1	—	—	2200	—	—	500
	Rhizoprionodon acutus	689	14	280	960	140	0.56	81	750	<0.001	54	—
	Rhizoprionodon taylori	546	—	—	—	1	all F	1	400	—	100	250
Dasyatidae	*Amphotistius annotata*	211.4	12	140	452	25	1.43	3	200	>0.5	24	—
	Dasyatis kuhlii	297.3	12	190	400	24	4.00	10	300	>0.5	8	160
	Dasyatis leylandi	182.2	3	110	400	206	1.05	162	180	>0.2	46	110
	Dasyatis sp. A	350	—	—	—	1	—	—	360	—	0	—
	Dasyatis thetidis	1162	129	800	1420	5	all M	1	—	—	—	350
	Himantura fai	1900	—	—	—	1	—	—	—	—	—	550
	Himantura granulata	960	—	—	—	1	—	—	—	—	—	280
	Himantura jenkinsii	890	150	300	1140	5	all M	1	—	—	—	—
	Himantura sp. A	350	65	80	1800	57	all F	12	—	—	—	—
	Himantura toshi	456	11	150	1330	235	4.17	52	400	<0.001	12	200
	Himantura uarnak	1055	132	290	1600	12	all F	2	—	—	—	280
	Himantura undulata	1117	131	400	1500	7	all F	1	—	—	—	200
	Pastinachus sephen	1076	53	450	2000	43	3.03	12	—	—	—	180
	Taeniura meyeni	1300	—	—	—	1	—	—	—	—	—	350
	Urogymnus asperrimus	850	106	530	1150	5	all M	2	—	—	—	—
Ginglymostomatidae	*Nebrius ferrugineus*	2400	—	—	—	1	—	—	2250	—	100	400
Gymnuridae	*Gymnura australis*	462	19	120	860	87	2.00	42	350	<0.001	24	—
Hemigaleidae	*Hemigaleus microstoma*	609	19	250	950	152	0.68	91	600	>0.5	47	300
	Hemipristis elongata	1340	190	1150	1530	2	all F	1	1100	>0.5	50	520
Hemiscylliidae	*Chiloscyllium punctatum*	668	23	230	1000	63	2.50	7	700	<0.001	52	170
Myliobatidae	*Aetobatus narinari*	625	125	500	750	2	all F	1	—	—	—	260
	Aetomylaeus nichofii	437	42	240	720	11	all F	3	—	—	—	170
Pristidae	*Anoxypristis cuspidata*	1930	193	1240	2550	8	all F	1	—	—	—	—
Rhinobatidae	*Rhinobatos typus*	1953	188	1500	2340	4	—	—	—	—	—	—
Rhynchobatidae	*Rhina ancylostoma*	1643	112	1010	2090	9	0.33	3	—	—	—	—
	Rhynchobatus djiddensis	869	36	230	2650	187	4.76	35	1100	<0.001	8	—
Scyliorhinidae	*Atelomycterus fasciatus*	300	0	300	300	2	—	—	320	—	0	—
Sphyrnidae	*Eusphyra blochii*	990	320	670	1310	2	—	—	1080	>0.5	50	450
	Sphyrna lewini	832	54	400	2400	37	all F	3	1400	<0.001	3	450
	Sphyrna mokarran	1780	457	400	2400	3	1.00	2	2100	>0.5	33	650
Stegostomatidae	*Stegostoma fasciatum*	1305	82	400	2000	26	0.80	3	1700	<0.001	23	200

Table 7

The percentage of elasmobranchs that died within the trawl net, recorded on research and crew-member observer surveys. "Combined sharks" refers to all species where total length was recorded; "combined rays" refers to all species where disc width was recorded; n = number of specimens measured.

		% dead					
Family	Taxa	Female	n	Male	n	Overall	n
	combined sharks	23	149	66	59	61	639
	combined rays	56	360	67	279	40	208
Carcharhinidae	*Carcharhinus dussumieri*	48	207	58	114	52	321
	Carcharhinus sorrah	73	15	50	8	65	23
	Carcharhinus tilstoni	78	40	85	33	82	73
	Rhizoprionodon acutus	75	44	86	72	82	116
Dasyatidae	*Dasyatis leylandi*	27	22	95	19	59	41
	Himantura toshi	43	40	78	18	53	58
Gymnuridae	*Gymnura australis*	31	26	75	8	41	34
Hemigaleidae	*Hemigaleus microstoma*	44	29	64	39	62	68
Rhynchobatidae	*Rhynchobatus djiddensis*	21	24	20	5	10	59

Table 8

The correlations between the criteria on 1) the susceptibility axis and 2) the recovery axis. * indicates significance at $P < 0.05$.

Susceptibility	Survival	Range	Day and night catchability	Diet	Depth range
Water column position	0.07	–0.18	0.13	0.67*	0.07
Survival		0.48*	0.07	–0.11	–0.00
Range			0.25	0.06	0.09
Day and night catchability				–0.15	0.04
Diet					0.05
Recovery	**Maximum size**	**Removal rate**	**Annual fecundity**	**Mortality index**	
Probability of breeding	0.07	0.25	0.16	0.08	
Maximum size		–0.22	–0.25	0.17	
Removal rate			–0.27	0.21	
Annual fecundity				0.12	

sharks and rays, particularly the smaller individuals, die within the trawl net (56%). The lower survival rates of male individuals is possibly because the males of most elasmobranch species are smaller than the females. The rhynchobatid *R. djiddensis* had a higher survival rate (90%) than most other species, whereas the lowest survival rate was seen in *C. tilstoni* and *R. acutus* (18%). Although the larger elasmobranchs appeared to have a higher within-net survival, in the commercial fishery these were the very individuals killed for their fins and therefore their mortality was ultimately higher than that predicted by their size alone. In 2001 the NPF introduced an industry-initiated ban on all shark products, so that the only mortality these species are subject to is that caused by the capture process. Differences between species in survival rates may influence changes in the relative abundance of species.

Assessment of the sustainability of elasmobranch species

Elasmobranchs, in general, are more susceptible to overfishing than are bony fishes, but there is likely to be a range of sensitivities among the species (Walker, 1998; Stevens et al., 2000). The process we applied in our study allowed us to examine these different sensitivities and to highlight those species whose populations were most likely to be affected by the NPF. The process was designed to deal with the high diversity of the bycatch and the

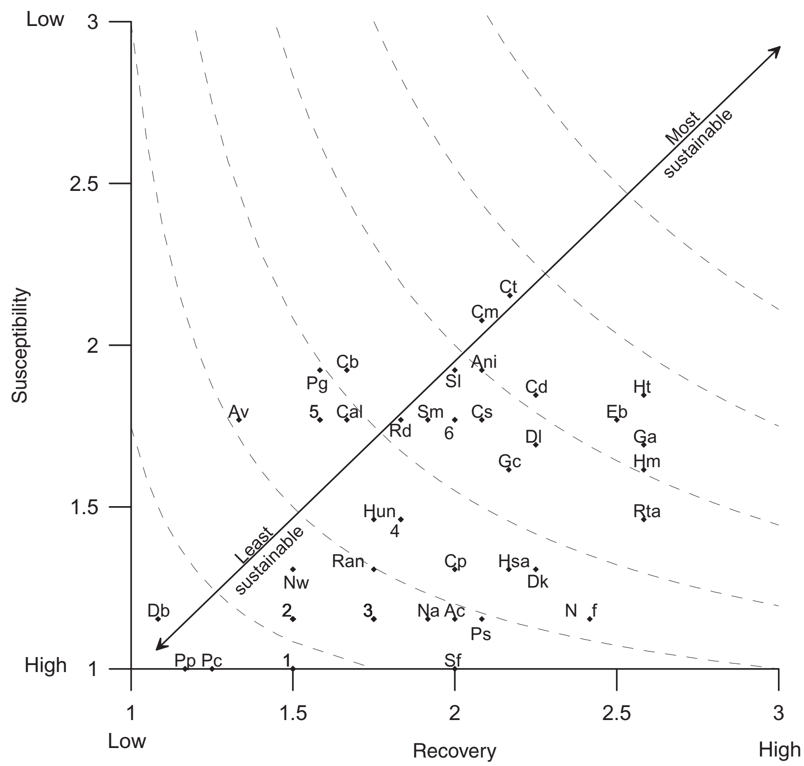

Figure 2

The ranking of elasmobranch species with respect to criteria that reflect their susceptibility to capture and mortality due to prawn trawling and their capacity to recover after depletion by trawling. These factors combine to reflect the relative ability of species to sustain capture as prawn trawl bycatch in the northern prawn fishery and therefore their relative priority with respect to research and management. Numbers refer to species combinations that fall together on the graph. (1=Hj, Pm, Pz; 2=Ca, Cle, Dt, Gsa, Ssa, Tm; 3=Af, Dsa, Hf, Hg Hua, Oo, Rty, Ua; 4=Cf, Aa; 5=Ana, Cli; 6=Rac, He). Explanations of the abbreviations for species are given in Table 3.

paucity of information available for most species. Our process was similar to that used by the International Union for the Conservation of Nature and Natural Resources (IUCN) red lists (IUCN, 1995) that categorize species with respect to the threat of extinction worldwide. The IUCN uses criteria on the extent of population decrease, area of occurrence, percentage of population that is mature, and the probability of extinction (IUCN, 1995). The IUCN criteria have been modified for application to marine fishes and to smaller geographic scales (Musick, 1998). With respect to elasmobranchs, several authors have examined the variable resilience of species to fishing pressure. These approaches have focused on life history characteristics that influence the recovery of populations, including reproductive and growth parameters (reviewed by Stevens et al., 2000). Our process is similar to these but focuses at the level of an individual fishery, incorporating fishery-specific information on the susceptibility of species to the fishery. Of significant importance with all methods is the ability to calculate the range of parameters required for a large number of species (Stevens et al., 2000). The semi-quantitative method used in our study maximizes what can be determined from the data available and enables consistency across the species. The criteria include characteristics that influence the probability of extinction of a species and its sensitivity to overfishing (McKinney, 1997: Carlton et al., 1999; Roberts and Hawkins, 1999; Stevens et al., 2000). Our analysis provides a process for highlighting gaps in information and for prioritizing species for future management and research. This process does not replace traditional methods of population assessment but provides a rapid assessment of the species, so that traditional methods can be focused on the high-risk species.

The species that were least likely to be sustainable in the bycatch of the NPF were *D. brevicaudatus, P. pectinata, P. clavata, P. microdon, P. zijsron,* and *Himantura jenkinsii* (Fig. 3). The pristids and *H. jenkinsii* had ranks of 1 on the susceptibility axis, the lowest possible rank, and *D. brevicaudatus* ranked 1.15 (Appendix 1). These species are demersal, are rare in the bycatch, and at least for the pristids (which have restricted depth distributions) are likely to be rare. Nothing is known about their sur-

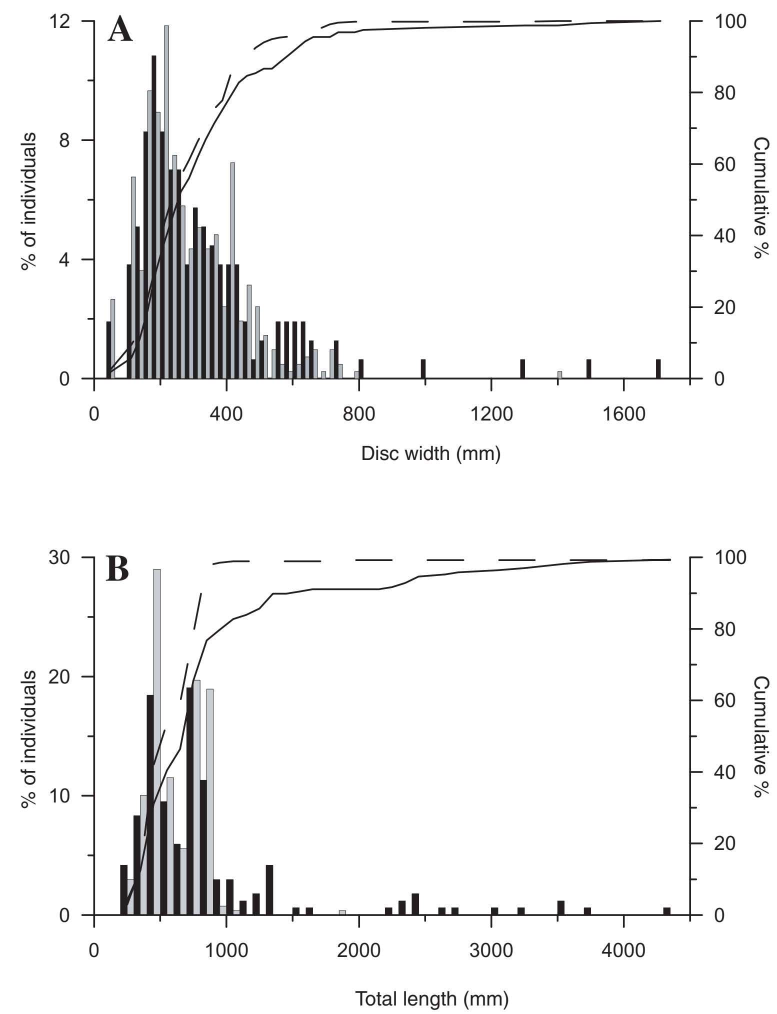

Figure 3

The length frequency and cumulative length frequency of rays (**A**) and sharks (**B**) caught in nets with a standard codend (black columns and solid line) and nets with a TED (grey columns and broken line).

vival. Their diets include benthic organisms and are likely to include commercial prawns; their range and day and night catchability is unknown. The combination of these factors means that these species are likely to occur in trawl grounds and that they are highly susceptible to capture and mortality due to trawlers. The recovery capacity of populations of these species is also low (Appendix 2). The rarity of the species in the bycatch means that no data are available to estimate the probability of breeding before capture, removal rate, total biomass, or the mortality index for most of these species, and they therefore received ranks of 1 for these criteria. In general these are large animals and are therefore likely to have slower recovery rates for their population than those of smaller species. The annual fecundity was low for all species.

The pristids are the focus of increasing international concern because their populations are declining worldwide (Stevens et al. 2000). They are rarely seen today in areas where they were previously abundant (Simpfendorfer, 2000). This decrease in pristid populations has resulted in four species being listed on the IUCN 1996 red list (Bailie and Groombridge, 1996). Of the species studied in our study, *P. pectinata* and *P. microdon* are listed as endangered. Recent demographic analysis of pristid populations has indicated that their recovery will take several decades even if they are given effective conservation (Simpfendorfer, 2000).

In comparison, the species that were most likely to be able to sustain capture in the bycatch of the NPF were *H. toshi, E. blockii, C. macloti,* and *C. tilstoni.* These species had a lower susceptibility to capture and mortality due to trawling (Appendix 1). With the exception of *H. toshi*, these are pelagic species and there is little likelihood of their capture in prawn trawls. For the species for which

Table 9

The mean size of elasmobranch species caught in nets with codends fitted with TEDs and with standard codends, and the ANOVA results from the comparison of these nets. "Combined sharks" refers to all species where total length was recorded; "combined rays" refers to all species where disc width was recorded. SE = standard error; *n* = number of trawls.

		Size (mm)			ANOVA results		
Species	Codend	mean	SE	*n*	*F*	df	*P*
Combined sharks	standard	887	59	168	4.25	1,569	0.0398
	TED	596	36	269			
Combined rays	standard	330	19	157	26.77	1,435	<0.0001
	TED	286	7	414			
Carcharhinus dussumieri	standard	844.4	96.4	60	26.88	1,139	<0.0001
	TED	489.1	13.8	81			
Rhizoprionodon acutus	standard	636.9	34.2	45	7.15	1,134	0.0084
	TED	724.2	17.4	91			
Hemigaleus microstoma	standard	708.9	148.5	23	2.77	1,79	0.0988
	TED	508.0	19.9	58			
Amphotistius annotata	standard	206.4	31.1	50	2.97	1,200	0.4395
	TED	169.8	3.4	156			
Himantura toshi	standard	371.0	19.4	51	0.60	1,200	0.4395
	TED	351.6	9.7	151			
Rhynchobatus djiddensis	standard	1076.9	125.6	19	20.81	1,41	<0.0001
	TED	611.6	32.3	24			

data were available, their survival was higher in trawls. The depth range of the species was wide and their catch rates during the day were the same as or higher than at night. This range provides partial refuge from the nighttime commercial trawling. The data available suggest that their recovery capacity is higher than that of most elasmobranch species (Appendix 2). Individuals of most of these species are likely to have bred before capture and they are smaller. These species were common in the bycatch, and estimates of their removal rate (which was low) and their mortality index (average) were therefore easy to determine. However, all species had low annual fecundities.

This assessment of the elasmobranch bycatch is an important first step in ensuring their sustainability because it provides a focus for future research and management. The current ranking is constrained, however, by the available data and by the assumptions outlined in the "Methods" section. The effect of the lack of species-specific information on the ranks should be taken into account because it may reduce the rank of some species. The application of our assessment has highlighted important information gaps, which should be the focus of research, particularly for the species that are least likely to be sustainable.

It is also important that the assessment of the sustainability of elasmobranch species is extended to include the impact of other fisheries in the region. There are, for instance, fisheries targeting sharks, as well as other fisheries that capture elasmobranchs as bycatch. Because elasmobranch species may have a wide distribution range, their populations could be impacted by several fisheries, which might create an unsustainable status for the population overall. For example, the pristids are likely to be impacted by the inshore and estuarine gillnet fisheries in this region.

The results of our analysis, it is to be hoped, will help in the management of elasmobranch species and in earmarking the least sustainable of these species. Future management may include the use of exclusion devices (TEDs and BRDs), closures, or further limits on retaining shark products. The compulsory introduction of TEDs and BRDs into the NPF in 2000 is likely to affect catch rates of elasmobranchs. The TEDs have the potential to exclude large individuals. However, the majority of elasmobranchs caught are <1000 mm (Fig. 3) and may escape through TEDs. The effectiveness of TEDs will depend on their configuration (particularly the width between the bars) and the size and shape of the bycatch species. *Rhynchobatus djiddensis,* a large, broad species, appeared to be excluded well by TEDs (Table 9). In comparison, the smaller rays and small, slim sharks were not excluded well (Fig. 3, Table 9). With the introduction of TEDs to the fishery, species-specific exclusion rates should be monitored so that these can be taken into account in assessing the sustainability of a species. Juveniles of many elasmobranch species are still likely to be captured and their capture could potentially have a large impact on their respective populations. The TEDs may also be ineffective for species, such as the pristids, that may tangle their saw in the net or the TED. Species and the life stages of species, for which exclusion devices are not effective, may require different management strategies, such as marine protected areas.

This research is the first large-scale assessment of its kind on elasmobranch bycatch. The results highlight the diversity of elasmobranch bycatch in the NPF and the species that are least likely to be sustainable. We have also highlighted the limited information available for making this assessment. However, our method was designed to maximize the use of the limited information. The process we have used is applicable to other fisheries and also across fisheries, particularly where bycatch diversity is high.

Acknowledgments

We thank the commercial fishermen who took the time to record their catch in logbooks and support this project. The skippers and crews of the boats on which our scientific observer sampled are also thanked for their cooperation and patience. We also thank the Northern Prawn Fishery Management Advisory Committee for its support; the Northern Prawn Fishery, Fishery Assessment Group for their participation in this process and feedback; C. Rose for collection of the crew-member observer data; and T. Walker for valuable comments on the manuscript. CSIRO Marine Research colleagues helped in many ways, M. Haywood, F. Manson and J. Bishop for assistance with the bioregion data and commercial effort data, C. Burridge and W. Venables for assistance with the statistical analysis; S. Blaber, G. Fry, D. Milton, J. Salini, J. Stevens and T. Wassenberg for constructive comments on the manuscript. We also thank the fishing, scientific, and electronics crew of the RV *Southern Surveyor* who made the research surveys possible. This project was funded by the Australian Fisheries Research and Development Corporation (Project no. 96/257) and CSIRO Marine Research.

Literature cited

Bailie, J., and B. Groombridge.
1996. IUCN red list of threatened animals, 448 p. IUCN (International Union for the Conservation of Nature and Natural Resources), Gland, Switzerland.

Bass, A. J., J. D. D'Aubrey, and N. Kistnasamy.
1973. Sharks of the east coast of southern Africa. I. The genus *Carcharhinus* (Carcharhinidae). Oceanographic Research Institute Investigation Report 33.

Bishop J., and D. Sterling.
1999. Survey of technology utilised in the northern prawn fishery, 48 p. AFMA (Australian Fisheries Management Authority), Canberra.

Blaber, S. J. M., D. T. Brewer, and A. N. Harris.
1994. Distribution, biomass and community structure of demersal fishes of the Gulf of Carpentaria, Australia. J. Mar. Freshwater Res. 45:375–396.

Bonfil, R.
1994. Overview of world elasmobranch fisheries. FAO Fisheries Tech. Paper 341, 119 p. FAO, Rome.

Brander, K.
1981. Disappearance of common skate *Raia batis* from Irish Sea. Nature 290:48–49.

Brewer, D. T., N. Rawlinson, S. Eayrs, and C. Burridge.
1998. An assessment of bycatch reduction devices in a tropical Australian prawn trawl fishery. Fish. Res. 36:195–215.

Carlton, J. T., J. B. Geller, M. L. Reaka-Kudla, and E. A. Norse.
1999. Historical extinctions in the sea. Annu. Rev. Ecol. Syst. 30:515–538.

Casey, J. M., and R. A. Myers.
1998. Near extinction of a large, widely distributed fish. Science 281:690–691.

Compagno, L. J. V.
1984a. FAO species catalogue. Vol. 4. Sharks of the world. An annotated and illustrated catalogue of shark species known to date. Part 1. Hexanchiformes to Lamniformes, 249 p. FAO, Rome.
1984b. FAO species catalogue. Vol. 4. Sharks of the world. An annotated and illustrated catalogue of shark species known to date. Part 1. Carcharhiniformes, 405 p. FAO, Rome.

Crocos, P. J., and G. J. Coman.
1997. Seasonal and age variability in the reproductive performance of *Penaeus semisulcatus* broodstock, optimising broodstock selection. Aquaculture 155:57–69.

Dulvy, N. K., J. D. Metcalfe, J. Glanville, M. G. Pawson, and J. D. Reynolds.
2000. Fishery stability, local extinctions and shifts in community structure in skates. Cons. Biol. 14:283–293.

Hall, S. J.
1999. The effects of fishing on marine ecosystems and communities, 274 p. Blackwell Science, Oxford.

Hueter, R. E.
1998. Science and management of shark fisheries—introduction. Fish. Res. 39:105.

IUCN (International Union for the Conservation of Nature and Natural Resources).
1995. IUCN red list categories, 21 p. IUCN, Gland, Switzerland.

Jennings S., J. D. Reynolds, and N. V. C. Polunin.
1999. Predicting the vulnerability of tropical reef fishes to exploitation: an approach based on phylogenies and life histories. Cons. Biol. 13:1466–1475.

Last, P. R., and J. D. Stevens.
1994. Sharks and rays of Australia, 513 p. CSIRO Publishing, Australia.

Lavery, S., and J. B. Shaklee.
1991. Genetic evidence for separation of two sharks, *Carcharhinus limbatus* and *C. tilstoni*, from Northern Australia. Mar. Biol. 108:1–4.

McKinney, M. L.
1997. Extinction vulnerability and selectivity: combining ecological and paleontolgical views. Annu. Rev. Ecol. Syst. 28:495–516.

McLoughlin, K., B. Wallner, and D. Staples.
1997. Fishery status reports 1996, 144 p. Bureau of Resource Sciences, Kingston, Australia.

Milton, D. A., S. A. Short, M. F. O'Neill, and S. J. M. Blaber.
1995. Ageing of three species of tropical snapper (Lutjanidae) from the Gulf of Carpentaria, Australia, using radiometry and otolith ring counts. Fish. Bull. 93:103–115.

Milton, D. A.
2001. Assessing the susceptibility to fishing of populations of rare trawl bycatch: sea snakes caught by Australia's Northern Prawn Fishery. Biol. Cons. 101:281–290

Musick, J. A.
1998. Endangered marine fishes: criteria and identification of north American stocks at risk. Fish. 23:28–31.

Roberts, C. M., and J. P. Hawkins.
1999. Extinction risk in the sea. Trends Envir. Ecol. 14: 241–246.

SAS.
2001. Logistic regression examples using the SAS system, version 6, first ed., 176 p. SAS Institute Inc., Cary, NC.
Simpfendorfer, C. A.
2000. Predicting population recovery rates for endangered western Atlantic sawfishes using demographic analysis. Environ. Biol. Fish. 58:371–377.
Sokal, R. R., and R. J. Rohlf.
1996. Introduction to biostatistics, 2nd edition, 363 p. Freeman and Company, New York, NY.
Somers, I.
1994. No resources, no fishery, prawns and their habitat. *In* Australia's northern prawn fishery (P. C. Pownall, ed.), p. 49–65. NPF 25, Cleveland, Australia.
Sparre, P., and S. C. Venema.
1992. Introduction to tropical fish stock assessment, part 1. FAO Fisheries Technical Paper 306/1, 376 p. FAO Rome.
Stevens, J. D., R. Bonfil, N. K. Dulvy, and P. A. Walker.
2000. The effects of fishing on sharks, rays and chimaeras (chondrichthyans), and the implications for marine ecosystems. ICES J. Mar. Sci. 57:476–494.
Stobutzki, I. C., M.J . Miller, and D. T. Brewer.
2001a. Sustainability of fishery bycatch: a process for dealing with highly diverse and numerous bycatch. Environ. Cons. 28:167–181.
Stobutzki, I. C., M. J. Miller, J. P. Jones, and J. P. Salini.
2001b. Bycatch diversity and variation in penaeid fisheries; the implications for monitoring. Fish. Res. 53:283–301.
Thackway, R., and I. D. Cresswell.
1998. Interim marine and coastal rationalization for Australia; an ecosystem-based classification for marine and coastal environments, version 3.3, 120 p. Environment Australia, Commonwealth Department of the Environment, Canberra.
Walker, T. I.
1998. Can shark resources be harvested sustainably? A question revisited with a review of shark fisheries. Mar. Freshwater Res. 49:553–572.
Walker, P.A., and J. R. G. Hislop.
1998. Sensitive skates or resilient rays? Spatial and temporal shifts in ray species composition in the central and north-western North Sea between 1930 and the present day. ICES J. Mar. Sci. 55:392–402.

Appendix 1

The ranking of elasmobranch species that occurred in the bycatch of the northern prawn fishery with respect to criteria that influence their susceptibility to capture and mortality due to prawn trawls. The weights of the criteria are shown in parentheses; * indicates where species-specific information was not available. The information was obtained from Compagno (19984a; 1984b), Last and Stevens (1994), and Froese and Pauly[6].

		Criteria						
Family	Species	Water column position (3)	Survival (3)	Range (2)	Day and night catchability (2)	Diet (2)	Depth range (1)	Susceptibility ranking
Dasyatidae	*Himantura jenkinsii*	1	1*	1	1*	1*	1	1.00
Pristidae	*Pristis clavata*	1	1*	1*	1*	1*	1	1.00
Pristidae	*Pristis microdon*	1	1*	1*	1*	1*	1	1.00
Pristidae	*Pristis pectinata*	1	1*	1*	1*	1*	1	1.00
Pristidae	*Pristis zijsron*	1	1*	1	1*	1*	1	1.00
Stegostomatidae	*Stegostoma fasciatum*	1	1*	1*	1	1	1	1.00
Scyliorhinidae	*Atelomycterus fasciatus*	1	1*	1	1*	1*	3	1.15
Carcharhinidae	*Carcharhinus amboinensis*	1	1*	1	1*	1	3	1.15
Carcharhinidae	*Carcharhinus leucas*	1	1*	1*	1*	1	3	1.15
Dasyatidae	*Dasyatis brevicaudatus*	1	1*	1*	1*	1*	3	1.15
Dasyatidae	*Dasyatis* sp. A	1	1*	1	1*	1*	3	1.15
Dasyatidae	*Dasyatis thetidis*	1	1*	1	1*	1*	3	1.15
Scyliorhinidae	*Galeus* sp. A	1	1*	1*	1*	1*	3	1.15
Dasyatidae	*Himantura fai*	1	1*	1	1*	1*	3	1.15
Dasyatidae	*Himantura granulata*	1	1*	1	1*	1	3	1.15
Dasyatidae	*Himantura uarnak*	1	1*	1*	1*	1*	3	1.15
Ginglymostomatidae	*Nebrius ferrugineus*	1	1*	1	1*	1	3	1.15
Carcharhinidae	*Negaprion acutidens*	1	1*	1	1*	1	3	1.15
Orectolobidae	*Orectolobus ornatus*	1	1*	1	1	1	3	1.15
Rhinobatidae	*Rhinobatos typus*	1	1*	1	1*	1*	3	1.15
Squatinidae	Squatina *sp. A*	1	1*	1*	1*	1*	3	1.15
Dasyatidae	*Taeniura meyeni*	1	1*	1	1*	1*	3	1.15
Dasyatidae	*Urogymnus asperrimus*	1	1*	1	1*	1*	3	1.15
Pristidae	*Anoxypristis cuspidata*	1	1*	1*	2	1*	1	1.15
Dasyatidae	*Pastinachus sephen*	1	1*	2	1*	1	1	1.15
Hemiscylliidae	*Chiloscyllium punctatum*	1	1*	2	1	1	3	1.31
Dasyatidae	*Dasyatis kuhlii*	1	1*	2	1	1*	3	1.31
Dasyatidae	*Himantura* sp. A	1	1*	2	1*	1*	3	1.31
Narcinidae	*Narcine westraliensis*	1	1*	1*	1*	2	3	1.31
Rhynchobatidae	*Rhina ancylostoma*	1	1*	2	1	1	3	1.31
Carcharhinidae	*Carcharhinus fitztroyensis*	3	1*	1	1*	1	1	1.46
Dasyatidae	*Amphotistius annotata*	1	1*	2	2	1*	3	1.46
Dasyatidae	*Himantura undulata*	1	1*	2	2	1*	3	1.46
Carcharhinidae	*Rhizoprionodon taylori*	1	1*	1	3	1	3	1.46
Carcharhinidae	*Galeocerdo cuvier*	3	1*	1	1*	1	3	1.62
Hemiscylliidae	*Hemigaleus microstoma*	1	1	3	1*	2	3	1.62
Dasyatidae	*Dasyatis leylandi*	1	2	3	1	1	3	1.69
Gymnuridae	*Gymnura australis*	1	2	3	2	1*	1	1.69
Carcharhinidae	*Carcharhinus sorrah*	3	1	2	1*	1	3	1.77
Carcharhinidae	*Rhizoprionodon acutus*	1	1	3	3	1	3	1.77
Rhynchobatidae	*Rhynchobatus djiddensis*	1	3	2	1*	1*	3	1.77

continued

Appendix 1 (continued)

		Criteria						
Family	Species	Water column position (3)	Survival (3)	Range (2)	Day and night catchability (2)	Diet (2)	Depth range (1)	Susceptibility ranking
Myliobatidae	*Aetobatus narinari*	3	1*	1	1*	2	3	1.77
Myliobatidae	*Aetomylaeus vespertilio*	3	1*	1*	1*	2*	3	1.77
Carcharhinidae	*Carcharhinus albimarginatus*	3	1*	1	1*	2	3	1.77
Hemiscylliidae	*Hemipristis elongatus*	3	1*	1	1*	2	3	1.77
Sphyrnidae	*Sphyrna mokarran*	3	1*	1	1*	2	3	1.77
Carcharhinidae	*Carcharhinus limbatus*	3	1	1*	1*	3	1	1.77
Sphyrnidae	*Eusphyra blochii*	3	1*	1	2	1	3	1.77
Carcharhinidae	*Carcharhinus dussumieri*	1	2	2	3	1	3	1.85
Dasyatidae	*Himantura toshi*	1	2	3	2	1	3	1.85
Myliobatidae	*Aetomyleus nichofii*	3	1*	2	1	2*	3	1.92
Carcharhinidae	*Carcharhinus brevipinna*	3	1*	1*	1*	3	3	1.92
Carcharhinidae	*Prionace glauca*	3	1*	1*	1*	3	3	1.92
Sphyrnidae	*Sphyrna lewini*	3	1*	1*	1*	3	3	1.92
Carcharhinidae	*Carcharhinus macloti*	3	1*	1	3	2	3	2.08
Carcharhinidae	*Carcharhinus tilstoni*	3	2	2	2	1	3	2.15

Appendix 2

The ranking of elasmobranch species that occurrred in the bycatch of the northern prawn fishery with respect to criteria that reflect their capacity to recover after depletion by trawling. The weights of the criteria are shown in parentheses; * indicates where species-specific information was not available. The information was obtained from Compagno (1984a; 1984b), Last and Stevens (1994), and Froese and Pauly[6].

		Criteria					
Family	Species	Probability of breeding (3)	Maximum size (3)	Removal rate (3)	Annual fecundity (2)	Mortality index (1)	Recovery ranking
Dasyatidae	*Dasyatis brevicaudatus*	1	1	1*	1	2	1.08
Pristidae	*Pristis pectinata*	1*	1	1*	2	1*	1.17
Pristidae	*Pristis clavata*	1*	2	1*	1*	1*	1.25
Myliobatidae	*Aetomylaeus vespertilio*	1*	2	1*	1*	2	1.33
Dasyatidae	*Taeniura meyeni*	1	1	3	1	1	1.50
Dasyatidae	*Himantura jenkinsii*	1*	2	2	1*	1	1.50
Carcharhinidae	*Carcharhinus amboinensis*	1	2	1	2	2	1.50
Carcharhinidae	*Carcharhinus leucas*	1	3	1*	1	1	1.50
Scyliorhinidae	*Galeus* sp. A	1*	3	1*	1*	1*	1.50
Narcinidae	*Narcine westraliensis*	1*	3	1*	1*	1*	1.50
Pristidae	*Pristis microdon*	1*	3	1*	1*	1*	1.50
Squatinidae	*Squatina* sp. A	1*	3	1*	1*	1*	1.50
Carcharhinidae	*Prionace glauca*	1*	2	1*	3	1*	1.58
Myliobatidae	*Aetobatus narinari*	1*	1	3	1	2	1.58
Carcharhinidae	*Carcharhinus limbatus*	1*	3	1*	1	2	1.58
Carcharhinidae	*Carcharhinus albimarginatus*	1*	2	2	2	1*	1.67
Carcharhinidae	*Carcharhinus brevipinna*	1*	3	1*	2	1*	1.67
Dasyatidae	*Dasyatis thetidis*	1*	2	3	1*	1	1.75
Pristidae	*Pristis zijsron*	1*	2	3	1*	1*	1.75
Dasyatidae	*Himantura fai*	1*	2	3	1*	1*	1.75
Dasyatidae	*Himantura granulata*	1*	2	3	1*	1*	1.75
Dasyatidae	*Himantura uarnak*	1*	2	3	1*	1	1.75
Dasyatidae	*Himantura undulata*	1*	2	3	1*	1	1.75
Orectolobidae	*Orectolobus ornatus*	1*	2	3	1*	1*	1.75
Dasyatidae	*Urogymnus asperrimus*	1	2	3	1	1	1.75
Scyliorhinidae	*Atelomycterus fasciatus*	2	2	2	1	1	1.75
Dasyatidae	*Dasyatis* sp. A	2	3	1	1*	1*	1.75
Dasyatidae	*Amphotistius annotata*	2*	1	3	1*	2	1.83
Rhynchobatidae	*Rhynchobatus djiddensis*	1	2	3	1*	2	1.83
Carcharhinidae	*Carcharhinus fitztroyensis*	2	2	2	1	2	1.83
Sphyrnidae	*Sphyrna mokarran*	2	1	3	2*	1	1.92
Carcharhinidae	*Negaprion acutidens*	3	2	1	2	1*	1.92
Rhynchobatidae	*Rhina ancylostoma*	1*	3	3	1*	1	2.00
Rhinobatidae	*Rhinobatos typus*	1*	3	3	1*	1	2.00
Pristidae	*Anoxypristis cuspidata*	1	3	3	1	1*	2.00
Hemiscylliidae	*Chiloscyllium punctatum*	1*	3	3	1*	1	2.00
Hemiscylliidae	*Hemipristis elongatus*	2	2	3	1	1	2.00
Carcharhinidae	*Rhizoprionodon acutus*	1	3	3	1	1	2.00
Stegostomatidae	*Stegostoma fasciatum*	2*	2	3	1*	1	2.00
Sphyrnidae	*Sphyrna lewini*	1*	2	3	2*	2*	2.00
Myliobatidae	*Aetomyleus nichofii*	1*	3	3	1	2	2.08
Carcharhinidae	*Carcharhinus macloti*	2	2	3	1	2	2.08

continued

Appendix 2 (continued)

		Criteria					
Family	Species	Probability of breeding (3)	Maximum size (3)	Removal rate (3)	Annual fecundity (2)	Mortality index (1)	Recovery ranking
Carcharhinidae	*Carcharhinus sorrah*	1	3	3	1*	2	2.08
Dasyatidae	*Pastinachus sephen*	3	1	3	1*	2	2.08
Carcharhinidae	*Galeocerdo cuvier*	2	1	3	3	2	2.17
Dasyatidae	*Himantura* sp. A	1*	3	3	1*	3	2.17
Carcharhinidae	*Carcharhinus tilstoni*	1	3	3	1	3	2.17
Carcharhinidae	*Carcharhinus dussumieri*	3	2	3	1	1	2.25
Dasyatidae	*Dasyatis kuhlii*	2	3	3	1	1*	2.25
Dasyatidae	*Dasyatis leylandi*	2	3	3	1*	1*	2.25
Ginglymostomatidae	*Nebrius ferrugineus*	3	2	3	2	1*	2.42
Sphyrnidae	*Eusphyra blochii*	2	3	3	2	2	2.50
Gymnuridae	*Gymnura australis*	3	3	3	1	2	2.58
Dasyatidae	*Himantura toshi*	3	3	3	1	2	2.58
Carcharhinidae	*Rhizoprionodon taylori*	3	3	3	1	2	2.58
Hemiscylliidae	*Hemigaleus microstoma*	2	3	3	2	3	2.58