CSIRO PUBLISHING

Marine and Freshwater Research, 2013, **64**, 1135–1155
http://dx.doi.org/10.1071/MF12292

Trawl impacts and biodiversity management in Shark Bay, Western Australia

Mervi Kangas[A,C] *and Sue Morrison*[B]

[A]Western Australian Fisheries and Marine Research Laboratories, PO Box 20, North Beach, WA 6920, Australia.
[B]Western Australian Museum, 49 Kew Street, Welshpool, WA 6106, Australia.
[C]Corresponding author. Email: Mervi.Kangas@fish.wa.gov.au

Abstract. Trawl by-catch species composition and impact of trawling on soft bottom habitats was investigated in Shark Bay over four seasons. Spatial and temporal variability in faunal abundance and assemblages were investigated for sites with varied levels of trawl intensity, including areas permanently closed to trawling. Environmental conditions were found to be more important in determining differences in faunal assemblages between sites than trawl intensity. In total, 241 fish and 360 invertebrate species were recorded in Shark Bay during this study. The 20 most abundant fish species contributed to 80% of the total number of fish caught overall and these occurred at 73 to 100% of the sites sampled whilst the 20 most abundant invertebrate species contributed to 88% of the total number of invertebrates caught and these occurred at 62 to 100% of sites sampled. Depletion experiments during two time periods were undertaken to determine the catchability (vulnerability) of fish and invertebrate species within these assemblages to better understand trawl impacts. These results, combined with the spatial and temporal distribution patterns of individual species, indicate that long-term trawl impacts can be mitigated by restricting trawling within current trawl areas that constitute 20–40% of the fishery area and for daily monitoring of the trawl fleet with the Vessel Monitoring System for adherence to permanent, spatial and temporal closures.

Additional keywords: biodiversity indices, bycatch, otter trawl selectivity, prawn (shrimp) fishery, seasonal variability.

Received 14 October 2012, accepted 11 May 2013, published online 14 October 2013

Introduction

Shark Bay is located on the central Western Australian coastline between ~24°45′S and 26°36′S. It is a shallow marine embayment open to the north, bounded on the western side by Edel Land Peninsula, which is connected to the mainland, and north of that by Dirk Hartog, Dorre and Bernier Islands. The southern part of the Bay is divided into eastern and western sections by the Peron Peninsula. Shark Bay covers an area of almost 13 000 km^2 (Logan and Cebulski 1970).

Shark Bay is in a hot, arid to semi-arid zone with mean daily temperatures ranging from 9.2 to 36.9°C. Water temperatures in the southern, shallower reaches range from 15 to 18°C in winter and 26 to 30°C in summer. The northern reaches are more influenced by the oceanic waters, with maximum autumn temperatures of 24–25°C and maximum winter 21°C. Rainfall is low, with an annual average of 232.6 mm at Carnarvon. Strong sea breezes occur, especially during summer, with mean monthly windspeeds ranging between 16.2 and 30.3 $km\,h^{-1}$ and gusts exceeding 177 $km\,h^{-1}$. These climatic conditions cause high evaporation rates between 2000 and 3000 mm that exceed the annual rainfall. There is, however, intermittent freshwater input from the Gascoyne and Wooramel Rivers into Shark Bay, particularly after heavy rainfall from summer cyclones or in winter.

Consequently, Shark Bay has a negative salinity gradient from oceanic salinity (35–40‰) at the seaward openings (Geographe Passage, Naturaliste Passage and South Passage), to hypersaline conditions (56–70‰) in the southern reaches of the two gulfs. This gradient has developed due to restricted water movement caused by the seagrass meadows and sills, combined with the low rainfall and high evaporation rate. The unusual salinity regime of Shark Bay provides suitable habitats for proliferation of unusual species, such as stromatolite-building microbes and the bivalve mollusc *Microfragum erugatum* (Tate, 1889), which can survive in extreme hypersaline conditions (Logan *et al.* 1974; Playford, 1990). The marine flora and fauna of Shark Bay are predominantly tropical, with a small number of temperate species, plus some species endemic to Western Australia. Many of the species are at either the northern or southern limit of their geographical range. A recent description of the environment and key faunal and floral features of Shark Bay is given by Kendrick *et al.* (2012).

Trawling commenced in Shark Bay in the early 1960s and the current Shark Bay prawn (shrimp) and scallop fisheries have an annual value between AUD25 and 30 million (Sporer *et al.* 2012). The prawn fishery targets western king prawns (*Penaeus latisulcatus* Kishinouye, 1896) and brown tiger prawns (*Penaeus esculentus* Haswell, 1879). It has operated under a limited-entry management regime since its inception with catches maintained within a range of 1000–2300 tonnes (t) per year using a comprehensive set of regulations that include limits on vessel numbers (presently 18 licenses), gear, zoning, closed seasons, extensive closed areas and real-time monitoring to maintain catch rate levels of spawning stock above a threshold reference point (Fletcher and Santoro 2011). The commercial prawn season generally commences in mid to late March and is closed by October and includes 5–12 days non-fishing around the full moon each month.

The scallop fishery is based on the saucer scallop, *Amusium balloti* Bernardi, 1861 (presently with 11 dedicated scallop boats), whilst the prawn fleet can also retain scallops, and both fleets operate under a catch share arrangement that was formalised in 2012. Annual scallop catches are typically highly variable and have ranged from 605 to 22 070 t whole weight, depending primarily on the naturally variable strength of recruitment flowing from the breeding season of the previous year (Joll and Caputi 1995*a*, 1995*b*). The length and timing of the season is determined by results of a fishery-independent pre-season survey, which allows the prediction of the following season's catch (Mueller *et al.* 2012). In recent years, the scallop season has commenced between March and May and has lasted between three and six weeks.

The World Heritage Area (Fig. 1) in Shark Bay was declared in 1991 (Department of Fisheries 2000); its nomination reflected the situation in the bay after at least 30 years of trawling, and it was recognised that trawling could co-exist alongside conservation values. This was partly due to the introduction, at the commencement of the fisheries, of the protection of significant areas of Shark Bay including the largest seagrass meadows in the world (Kirkman and Walker 1989; Walker 1989, 1990; Walker and Prince 1987) as well as inshore shallow areas including those adjacent to Bernier/Dorre Islands (Fig. 1), which are nurseries for finfish, crustaceans and molluscs (Fletcher and Santoro 2011).

Trawling is recognised as non-selective (Saila 1983; Andrew and Pepperell 1992; Tonks *et al.* 2008) compared with most other fishing practices. When trawling occurs within a highly valued natural asset, with significant community interest and scrutiny, it requires management that includes cost effective, robust monitoring systems that demonstrate that trawl fishing impacts remain at acceptable levels. These measures also need to maintain untrawled areas within each habitat type with their related species assemblages. As a sampling method, demersal trawling has limitations in describing the overall biodiversity of a region. This is because trawl nets do not sample all species effectively, but it is an appropriate method for assessing trawl effects on biodiversity.

The high species diversity in prawn trawl by-catch is a challenge to monitoring and management (Stobutzki *et al.* 2000, 2001*a*, 2001*b*). There are a large number of taxa in low abundance, with the majority of species being uncommon and many having very little biological information available. The practicality of evaluating the sustainability of each by-catch species using traditional stock assessment methods is low or impossible. Effort to physically reduce overall by-catch (Hall 1999; Broadhurst *et al.* 1997) and increase survival of the by-catch component in the Shark Bay trawl fisheries, is through use of by-catch reduction devices (BRDs) in the nets and use of in-water hopper systems for holding of catch before processing. The Australian Government's *Environment Protection and Biodiversity Conservation Act 1999* imposes requirements on Australian trawl fisheries that may capture threatened species such as turtles. The incorporation of turtle exclusion devices (grids) in nets were fully implemented in Shark Bay during 2002 and were shown to exclude nearly all (95–100%) large animals, including sharks, rays and turtles, in Shark Bay (Kangas and Thomson 2004). Secondary fish escape devices such as square mesh panels were also trialed from 2000 and became compulsory in nets in the Shark Bay prawn fishery in 2004. Square mesh panels were shown to potentially reduce smaller fish species between 20–75%, with some individuals being reduced by over 90% (Broadhurst *et al.* 1997, 2002; Kangas and Thomson 2004).

Since by-catch cannot be eliminated entirely, it is important to determine and monitor which species can or cannot sustain the impact of fishing and which species may be suitable as indicator species to reflect trawl impacts on the total suite of species in by-catch.

This study was conducted between 2002 and 2003 and provides baseline data of faunal abundance and composition in Shark Bay in areas that are both currently open to trawling and adjacent areas that are closed to trawling. Information on faunal assemblages before any trawling commencing (before 1960s) in the region is not available.

In areas open to trawling, detailed daily logbooks are available from the trawl fleet to determine the amount of effort expended annually on these grounds, and consequently fishing intensity can be compared with faunal abundance and diversity indices. Some of the areas now closed to trawling have never been trawled, whereas other areas were trawled during the early history of the fishery, providing an additional comparison between levels of trawling. Within the trawl grounds themselves, there are different levels of trawl activity due to spatial and temporal closures, allowing for comparisons between trawled areas at various trawl effort levels. To enable a more comprehensive assessment of trawl impacts on by-catch species biodiversity, depletion experiments were undertaken to assess by-catch species catchability. The use of repeated trawling over the same area has been undertaken by several researchers (Joll and Penn 1990; McKeown and Gordon 1997; Gordon *et al.* 1997; Poiner *et al.* 1998) to describe the depletion effects on target species (Joll and Penn 1990; Pitcher *et al.* 2000; Wassenberg *et al.* 2002; Burridge *et al.* 2003) or on both target and by-catch species (Poiner *et al.* 1998).

High variability in abundance in natural populations is common, particularly in species that are relatively short lived. Sampling at different times during the year can provide a representative picture of the mean abundance for a region (Stewart-Oaten *et al.* 1986; Underwood 1993). In order to understand changes in biodiversity in trawl by-catch in trawled and untrawled areas, some understanding of seasonal and annual variability in distribution and abundance of species is required. Also, in order to determine long-term monitoring strategies, the timing of monitoring needs to cover as many seasons and years as possible. Some understanding of seasonal cycles in species abundance is required so that these can be considered when interpreting results. The catching efficiency of the trawl gear may also vary seasonally on by-catch, as it does on the target species,

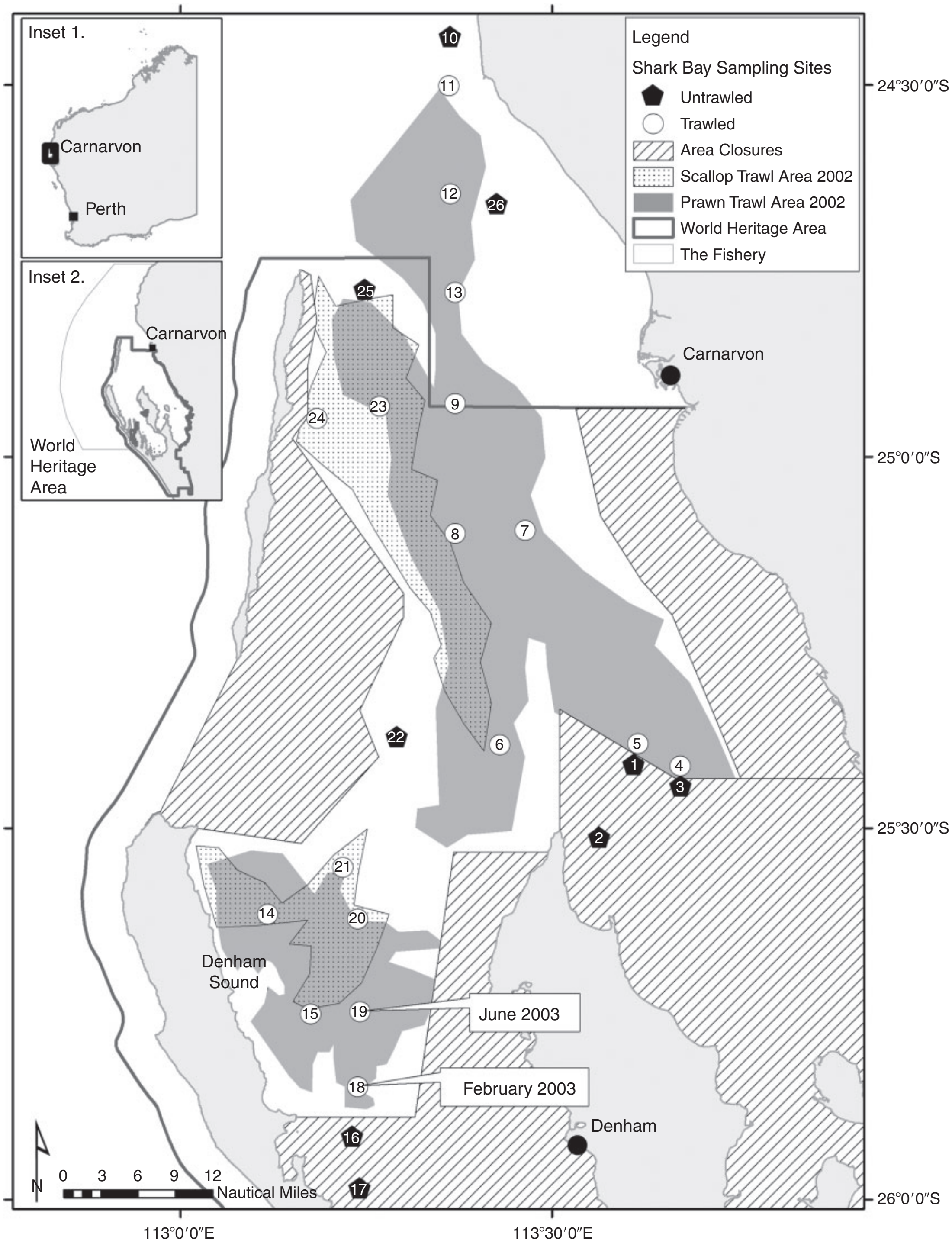

Fig. 1. Shark Bay and the location of sampling sites and the two sites for depletion experiments conducted in Denham Sound in February and June 2003. The hatched areas are trawl closures and the shaded areas are main trawl grounds. Inset 1 WA showing the Shark Bay region. Inset 2 Shark Bay indicating the extent of the Shark Bay prawn fishery and the World Heritage Area boundary.

whose catchability is influenced by for example, moon phase, water temperature and/or movement patterns of species (Penn 1984; Penn and Caputi 1986; Yousif 2003; Addison *et al.* 2003; Bishop *et al.* 2008; Currie *et al.* 2011; Montgomery *et al.* 2012).

The aim of this study is to provide data on trawl by-catch in Shark Bay that can be used to assist management in attaining biologically sustainable fisheries in the region and to inform other trawl fisheries in a broader context.

Methods

Site selection

Commercial daily logbooks provide shot by shot spatial information of fishing activity. This was used for the 2000 and 2001 fishing seasons to map trawled and adjacent untrawled areas. Sites representing varying levels of trawl effort were then selected from both prawn and scallop grounds that are spatially separate in parts of Shark Bay and overlapping in others (Fig. 1), and adjacent areas that were closed or open but untrawled. The amount of effort actually applied within 0.5 nautical mile (nm) of the sampling site was then assessed using daily logbooks for 2002 and 2003 seasons for the sampling sites (Fig. 2). All boats

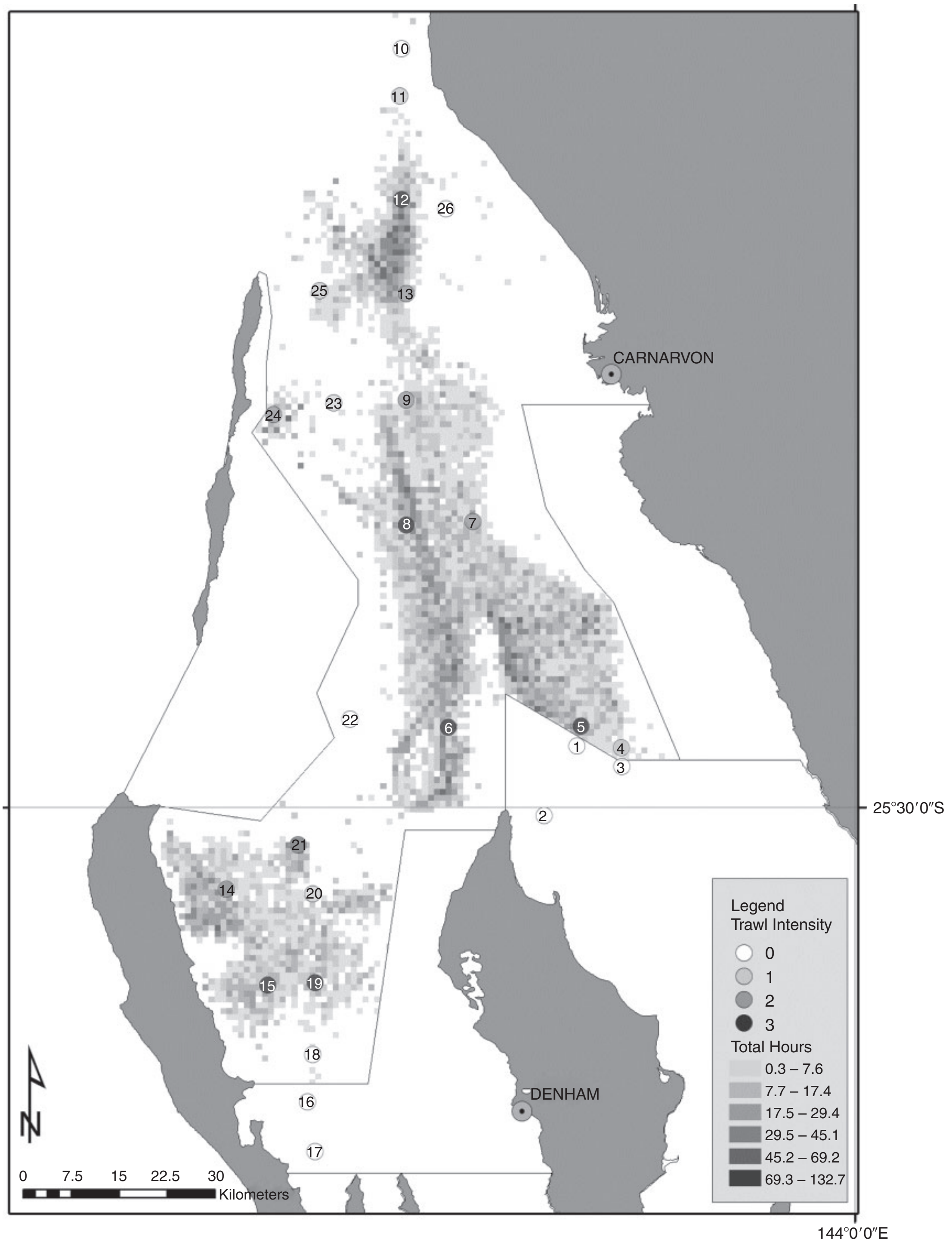

Fig. 2. Shark Bay and trawl intensity during October 2002 to November 2003 indicating hours trawled per 0.5 nm block and trawl intensity categories for each sampling site.

are equipped with a 'Vessel Monitoring System' (VMS) and this information was used to verify vessel positions.

The sampling design was based on selecting a range of sites that encompassed the spatial extent of Shark Bay and that had varying levels of fishing effort (Fig. 2). The hours of trawling from September 2002 to November 2003 were categorised as: zero – no trawling, 1 – low (1–50 h of trawling), 2 – medium (51–200 h of trawling) and 3 – high (> 200 h of trawling). The focus was on soft bottom trawlable habitats and, although latitudinal gradients were incorporated, it was not intended to sample habitats that were not trawlable (i.e. highly structured areas such as seagrass and sponge garden habitats). Twenty-six sites were selected, with four sites representing primarily scallop trawl grounds, 13 sites representing primarily prawn trawl grounds and six areas that are permanently closed to trawling (three since the late 1960s and three since 1990) and three sites very lightly trawled or untrawled in the last 10 years (Fig. 2). These sites were considered to effectively cover the main trawl habitats over the major environmental gradients that exist in Shark Bay and the sites selected represent the broad characteristics of soft-bottom habitats. All of the 26 site locations were fixed for the whole survey and sampled during three different seasons. Using fixed sites instead of a randomised sampling design has some limitations but these are addressed by the analyses conducted. To examine seasonal and annual faunal abundance variation in Shark Bay, sampling trips were undertaken in October/November 2002 and during the start (February/March), middle (June/July) and end (October/November) of a typical trawl season in 2003, resulting in each site being sampled four times.

Trawl methods

Every season, three 10-min trawls (shots) were undertaken at each site except when weather or gear fouling prevented this (2 sites in October 2002, 5 sites in February 2003, 5 sites in June 2003 and 4 sites in October 2003), when only one or two shots were completed. On average each trawl covered a distance of 0.5 nm but precise trawl distance was calculated using the trawl start and end latitude and longitude positions. The nets were twin rig demersal otter trawl nets with a six-fathom (10.97 m) headrope length. The net mesh size was 50 mm with 45 mm mesh cod ends. Sampling was carried out at night (1830 hours to 0500 hours). The timing simulated commercial prawn trawling activities. For each trawl, all species of fish and invertebrates were identified, counted and abundance determined as number per nm trawled. At each site, sea surface salinity and water temperature were measured and depth recorded.

Data analysis

Faunal assemblages

Non-metric multi-dimensional scaling (MDS) ordinations were undertaken to examine variation in the fish and invertebrate assemblages (PRIMERv6, Clarke and Warwick 2001). For each pair of samples, a simplified Morisita's index of similarity (Horn 1966) was calculated using the catch rates of individual species (number per nm trawled). Catch rates were square-root transformed before similarity values were calculated to reduce the variance. The fish and invertebrates were examined separately. Species that occurred at one site only were removed.

Richness, evenness and diversity

Richness, evenness and diversity indices were calculated using PRIMERv6 for the sites within the assemblages identified. Margalef's richness index (Margalef 1958) was used to examine fish and invertebrate species richness for each site for all sampling periods and analysis of variance applied to check for significant differences. The richness index (d) incorporates the total number of individuals (N) and is a measure of the total number of species (S) present for a given number of individuals: $d = (S - 1)/\log N$.

Pielou's evenness index (Pielou 1975) was used to examine the equitability or how evenly the individuals are distributed among the different species: $J' = H'/\log S$, where H' is the Shannon diversity index. Diversity indices take into account species richness and evenness. Two common diversity indices were calculated. The Shannon (or Shannon–Wiener) diversity index: $H' = -\sum_i p_i \ln(p_i)$, where p_i is the proportion of the total count arising from the ith species and the Simpson's index (Simpson 1949): $1 - \lambda' = 1 - \{\Sigma_i N_i(N_i - 1)\}/\{N(N - 1)\}$, where N_i is the number of individuals of species i. It represents the probability of two randomly chosen individuals being different species and ranges from 0 (low diversity) to almost 1 (high diversity).

To account for the unbalanced data (unequal number of observations per treatment), analysis of variance (ANOVA) tests, using TYPE III Sum of Squares was carried out with 95% confidence interval (expected value for the arithmetic means if the experimental design was balanced).

The DistLM routine (Primer 6) was also used to analyse faunal assemblages for each site incorporating environmental variables (salinity, water temperature and depth) and whether the site was trawled or untrawled for 2003 sampling periods combined. This routine provides quantitative measures and tests of the variation explained by the variable(s).

Environmental factors

The BEST procedure (Clarke and Ainsworth 1993) in PRIMERv6 was used to find which environmental variable out of depth, water temperature or salinity was most closely correlated with species distribution, diversity and abundance patterns. The BIO-ENV procedure amalgamated in BEST was chosen to carry out a full search of all possible combinations of the environmental variables. The environmental data were first averaged (for all sampling periods) for each site. The data were standardised and normalised before analysis. The resemblance matrix obtained for the species assemblage from clustering analysis was used in BEST to compare with the resemblance matrix calculated from Euclidean distance, resulting in Spearman rank correlation values.

Seasonal variability in faunal abundance and diversity indices

Permutation tests for multivariate analysis of variance (PERMANOVA) (Anderson 2001) were used to analyse the Bray–Curtis similarity index for each fish and invertebrate sample taken at trawled and untrawled sites. Factors considered in the PERMANOVA were trawled/untrawled, season and their two-way interaction. A fourth root transformation was applied to the sample data before calculating the associated Bray–Curtis index. Type 3 sum of squares are presented due to the data being unbalanced.

Spatial and temporal variation of some species

The spatial distribution and abundance of some of the more abundant fish and invertebrate by-catch species were looked at in detail and included species that were shown to have high, moderate and low catchability (vulnerability).

Relative fish species abundance related to trawl effort

To determine the power to detect differences with fish abundance with respect to trawl effort, ANOVA (Statistica) was conducted using the square root of the 'relative' catch rates of fish families for combined sites for the four trawl effort categories (0,1,2,3). Fish species were grouped into families to reduce the dataset and those families that had abundance at less than 2.5 per nm were removed from the dataset, resulting in 32 fish families. The relative catch rates were derived using a mean catch rate for sampling periods. Post hoc tests (Student–Newman–Keuls) were conducted to determine which levels of effort were significant.

Depletion estimates

Two depletion experiments were conducted in Denham Sound (DS) between 28 February and 3 March 2003 at site 18, and between 25 and 28 June 2003 at site 19 (Fig. 1). The water depth ranged between 16.8 and 17.2 m in February and 17.0 and 17.5 m in June over typical prawn trawl areas with primarily sand substrate.

Two depletion experiments were each conducted over four nights. In February the area was bounded by 25°9.700′ and 25°50.450′S and 113°14.600′ and 113°14.719′E and in June by 25°44.500′ and 25°45.250′S and 113°14.000′ and 113°14.119′E. The area trawled was 925 m × 192 m and consisted of completing 16 parallel steering lines (sweeps) using twin 11 m prawn nets with 50 mm stretched mesh and 45 mm in the cod-end. The seabed contact of the trawls was provided by a 10-mm ground chain positioned slightly ahead (two links) of the ground rope. The opening of each net under normal operational conditions was estimated to be 60% of the headrope length and the total width swept by each trawl net (including the two otter boards and short leg ropes) was estimated to be 8 m (Joll and Penn 1990).

The area delineated was covered by trawling north, then south with the gear overlapping the centre of the previous track so that all the area was covered. This was repeated until all 16 sweeps were completed. The gear was deployed and retrieved just outside the delineated area so that it was completely covered. Each sweep was 10 min in duration and all the fish (except venomous fish in families Scorpaenidae, Plotosidae and Siganidae) and invertebrates were sorted and numbers counted after every second sweep (2 sweeps sorted at a time) to even out any effects of trawling in different directions. Due to the potential mobility of some species, the outer four pairs of sweeps on the eastern and western edges were not included in the analysis so that immigration and emigration were minimised for most species. Disposal of catches after processing was made well clear of the experimental area.

A modification of the Leslie model was used (Ogle 2011) with the initial number of fish/invertebrates in a population denoted by N_0. The number of fish/invertebrates remaining in the closed population at the start of the tth removal is the initial population size minus the cumulative catch before the tth removal K_{t-1}. Thus,

$$N_t = N_0 - K_{t-1} \tag{1}$$

where

$$K_{t-1} = C_1 + C_2 + \ldots + C_{t-1} = \sum_{i=1}^{t-1} C_i$$

where C_i is the catch for the ith removal and $t > 0$ and $K_0 = 0$. In addition, assume that catch-per-unit-effort (CPUE) in the tth removal event is simply proportional to the surviving population at the time of the tth removal event i.e.

$$\frac{C_t}{f_t} = qN_t \tag{2}$$

where f_t is the level of effort for the tth removal and q is a proportionality constant typically defined as the catchability coefficient. The catchability coefficient represents the fraction of the population that is removed by one unit of fishing effort (one night of fishing effort). The Leslie method model is derived by substituting (Eqn 1) into (Eqn 2) for N_t and simplifying,

$$\frac{C_t}{f_t} = q(N_0 - K_{t-1}) \tag{3}$$

The last expression of (Eqn 3) is in the form of a linear model ($y = ax + b$.) where CPUE is the response (or y) variable, K_{t-1} is the explanatory (or x) variable, q is a constant (i.e. the magnitude of the slope), and qN_0 is a constant (i.e. the intercept). Thus, the negative of the slope of this model is an estimate of the catchability coefficient $\hat{q}$. The estimated initial population size, $\hat{N}_0$, is found by dividing the estimated intercept by $\hat{q}$.

Confidence intervals of estimated parameter

Assuming normal distributions, confidence intervals for q were derived from the slope and for N_0 were derived from the regression results with the confidence interval for N_0 estimated by the ratio of two random variables. The standard error of N_0,

$$SE(\hat{N}_0) = \frac{s_{y/x}}{\hat{q}} \sqrt{\left[\frac{1}{n} + \frac{(\hat{N}_0 - \bar{K})^2}{(n-1)s_K^2}\right]} \tag{4}$$

where $\bar{K}$ is the mean cumulative catch, s_K^2 is the variance of the cumulative catch and $s_{y/x}$ is the standard deviation about the regression line (Krebs 1999).

Results

In total, 241 fish and 360 invertebrate species were recorded in Shark Bay during this study (Kangas *et al.* 2007). The 20 most abundant fish species contributed to 80% of the total

Table 1. Twenty most abundant (number per nm trawled) fish species in Shark Bay in 2002 and 2003 and proportion of sites in which they were caught

Family	Species	Common name	Ave. no per nm	% sites
Monacanthidae	*Paramonacanthus choirocephalus*	Leatherjacket, hair-finned	447	100
Mullidae	*Upeneus asymmetricus*	Goatfish, asymmetrical	438	100
Terapontidae	*Pelates quadrilineatus*	Trumpeter	392	100
Lethrinidae	*Lethrinus genivittatus*	Emperor, threadfin	303	81
Tetraodontidae	*Torquigener pallimaculatus*	Toadfish, orange-spotted	152	100
Scorpaenidae	*Paracentropogon vespa*	Scorpionfish, bullrout	146	81
Callionymidae	*Callionymus goodladi*	Stinkfish, goodlad's	136	96
Monacanthidae	*Colurodontis paxmani*	Leatherjacket, Paxman's	106	77
Nemipteridae	*Pentapodus vitta*	Monocle bream, western Butterfish	105	77
Sillaginidae	*Sillago robusta*	Whiting, robust	101	92
Leiognathidae	*Leiognathus leuciscus*	Ponyfish, whipfin	93	85
Harpodontidae	*Saurida undosquamis*	Lizardfish, large-scaled grinner	83	100
Bothidae	*Engyprosopon grandisquama*	Flounder, spiny-headed	78	100
Scorpaenidae	*Apistus carinatus*	Scorpionfish, long-finned waspfish	51	88
Gerreidae	*Gerres subfasciatus*	Roach/banded silver biddy	50	81
Lethrinidae	*Lethrinus punctulatus*	Emperor, blue-spotted	48	77
Monacanthidae	*Monacanthus chinensis*	Leatherjacket, fan-bellied	47	81
Mullidae	*Upeneus tragula*	Goatfish, bar-tailed	45	77
Sillaginidae	*Sillago burrus*	Trumpeter whiting	42	73
Pinguipedidae	*Parapercis nebulosa*	Grubfish, red-barred	31	85

number of fish caught overall and these occurred at 73 to 100% of the sites sampled (Table 1). The 20 most abundant invertebrate species contributed to 88% of the total number of invertebrates caught and these occurred at 62 to 100% of sites sampled, except for the ascidian *Herdmania pallida* (Heller, 1878), which was only found in site 14 (Table 2, Fig. 1). Seventy two species of fish (30%) and 173 species (48%) of invertebrates were uncommon and were only caught in one or two sites during the study.

Faunal assemblages

Pooled data for 2002 and 2003 indicated three main groups of sites for fish (Fig. 3) and invertebrate (Fig. 4) assemblages. Each grouping contained both trawled and untrawled sites. Site 22, however, had completely different assemblages, with several fish and invertebrate species much more abundant (such as the fish *Colurodontis paxmani* Hutchins, 1977, *Monacanthus chinensis* (Isbeck, 1765), *Pteragogus enneacanthus* (Bleeker, 1853) and invertebrates *Colochirus quadrangularis* Troschel, 1846, *C. crassus* Eckman, 1918, *Breynia desorii* Gray, 1851 and unidentified ascidians) compared with other sites. This was the only site to have extensive dense meadows of wireweed *Amphibolis antarctica* (Labillardiere, 1807).

Environmental factors

Site grouping similarities were evident for depth (Fig. 5*a*) and temperature (Fig. 5*b*) for fish assemblages. Group 1 sites were shallower with cooler water temperatures whereas Group 3 sites were deeper with warmer water temperatures. The Spearman rank correlation between water depth and temperature matrix and the fish abundance matrix was 0.67, indicating a moderate correlation for fish abundance. For invertebrates, the resemblance

Table 2. Twenty most abundant (number per nm trawled) invertebrate species in Shark Bay in 2002 and 2003 and proportion of sites in which they were caught

Family	Species	Common name	Ave. no per nm	% sites
Penaeidae	*Metapenaeopsis sp.*	Coral prawn	441	100
Pectinidae	*Amusium balloti*	Saucer scallop	403	73
Penaeidae	*Penaeus latisulcatus*	King prawn	231	100
Pectinidae	*Annachlamys flabellata*	Fan scallop	159	85
Portunidae	*Portunus armatus*	Crab, blue swimmer	139	100
Penaeidae	*Penaeus esculentus*	Brown tiger prawn	90	88
Portunidae	*Portunus rubromarginatus*	Swimmer crab	87	100
Portunidae	*Portunus tenuipes*	Swimmer crab	61	85
Penaeidae	*Metapenaeopsis crassissima*	Coral prawn	53	77
Ascidiacea	*Ascidiacea*	Ascidian	49	85
Ascidiacea	*Herdmania pallida*	Ascidian	42	4
Philinidae	*Philine* sp.	Sea slug	40	81
Penaeidae	*Metapenaeus dalli*	Western school prawn	38	46
Penaeidae	*Metapenaeus endeavouri*	Endeavour prawn	36	62
Cucumariidae	*Colochirus quadrangularis*	Holothurian	34	69
Scyllaridae	*Eduarctus martensii*	Slipper lobster	33	81
Portunidae	*Thalamita sima*	Swimming crab	19	92
Cucumariidae	*Colochirus crassus*	Holothurian	19	96
Portunidae	*Portunus hastatoides*	Swimmer crab	18	62
Portunidae	*Charybdis feriata*	Coral crab	12	88

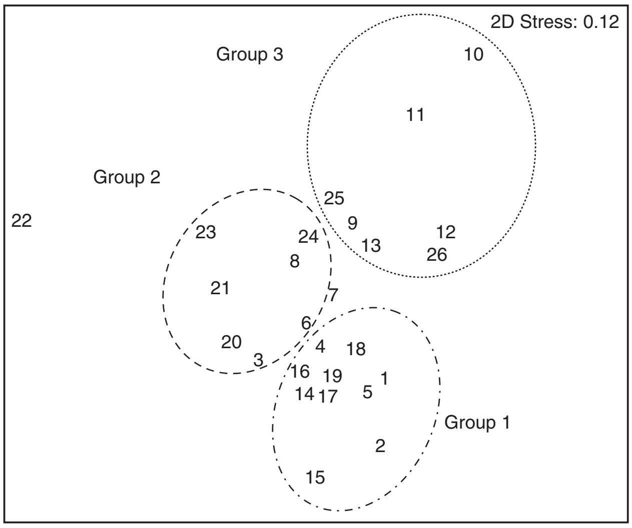

Fig. 3. MDS of fish species assemblages in Shark Bay for the 26 sites sampled in Shark Bay in 2002 and 2003.

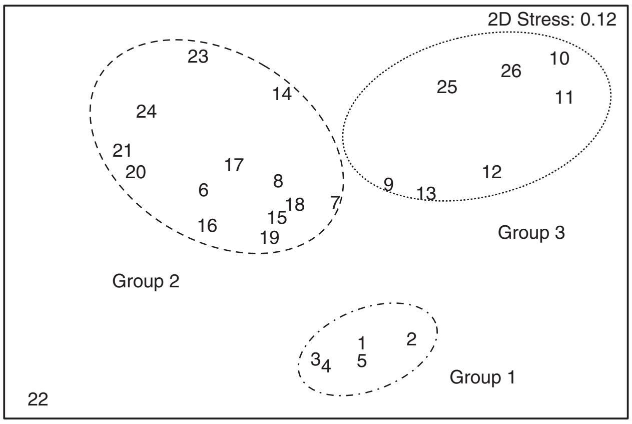

Fig. 4. MDS of invertebrate species assemblages in Shark Bay for the 26 sites sampled during 2002 and 2003.

matrix for salinity (Fig. 5*c*) and temperature (Fig. 5*d*) matched with the resemblance matrix of the species assemblage, with a moderate Spearman rank correlation of 0.51.

Diversity indices

Fish species

Both diversity indices had the highest variation explained by salinity (Shannon's 23% ($P = 0.0001$), Simpson's 16%, ($P = 0.0005$)) with the variation attributed to sites being trawled or untrawled being minor and not significant (Shannon's, $P = 0.64$, Simpson's, $P = 0.37$). The highest variation observed for the Margalef's richness index was with depth (11%, $P = 0.004$), with only 6% of the variation attributed to sites being trawled or untrawled ($P = 0.038$). The highest variation for Pielous's evenness index was 11% for salinity ($P = 0.0041$) with an additional 9% variation explained by being trawled or untrawled ($P = 0.0080$).

Invertebrate species

Both diversity indices had the highest variation explained by depth (Shannon's 33% ($P = 0.0001$), Simpson's 40% ($P = 0.0001$)) with other variables not being significant. The highest variation observed for Margalef's richness index was with depth (20%, $P = 0.0003$) with ~7% of the variation attributed to sites being trawled or untrawled ($P = 0.022$). When the other environmental variables were removed from the analysis and only depth and trawled/untrawled were fitted, then the variation attributed to sites being untrawled or trawled increased to 14% ($P = 0.0002$). The highest variation for Pielous's evenness index was 32% for depth ($P = 0.0001$) with no other variables being significant.

Fish assemblages

There were significant differences in the species evenness ($P < 0.01$), the Shannon's diversity index ($P < 0.01$) and Simpson's diversity index ($P < 0.01$) for the trawled and untrawled sites within Group 1. These were higher in the untrawled sites. Significant differences were also seen in the species richness ($P < 0.01$) and Shannon's diversity index ($P = 0.013$) for the trawled and untrawled sites within Group 3 but the values were higher in the trawled sites (Fig. 6*a–d*). There were too few untrawled samples in Group 2 for comparative analysis.

Invertebrate assemblages

There were no significant differences in the diversity measures for the trawled and untrawled sites within Groups 1 and 2 for any of the invertebrate assemblages (Fig. 7*a–d*). However, there were significant differences in the species richness ($P < 0.01$), the Shannon's diversity index ($P < 0.01$) and Simpson's diversity index ($P < 0.01$) for the trawled and untrawled sites within Group 3 with trawled sites having higher indices.

Seasonal faunal abundance variation in Shark Bay

Between and within seasons variation in abundance trends were seen in Shark Bay for both fish and invertebrates (Figs 8, 9). Permanovas indicated significant differences between trawled and untrawled sites between seasons (Tables 3*a*, *b*) but not for their interaction. The R^2 value is low, indicating that site differences are likely to be more important than trawled/untrawled differences. Significant differences were observed between trawled and untrawled sites between February 2003 and November 2003 with a decline in overall fish abundance. This decline was primarily attributed to a reduction in abundance at the majority of sites for five species; *Lethrinus genivittatus* Valenciennes, 1830, *Paramonacanthus choirocephalus* (Bleeker, 1851), *Pelates quadrilineatus* (Bloch, 1790), *Torquigener pallimaculatus* Hardy, 1983 and *Upeneus asymmetricus* Lachner, 1954 (Figs 12*c*, 14*b*,*c*,*d*).

For invertebrates, a significant increase was observed in abundance between November 2002 and February 2003 for both trawled and untrawled sites, for example Sepiidae (Fig. 11*c*). A significant decline in abundance was then observed between February 2003 and June 2003, with no further decline observed by November 2003. This was attributed to the very abundant species *A. balloti*, *P. latisulcatus*, *Portunus rubromarginatus* (Lanchester, 1900) (Fig. 14*a*) and *Herdmania pallida*, the

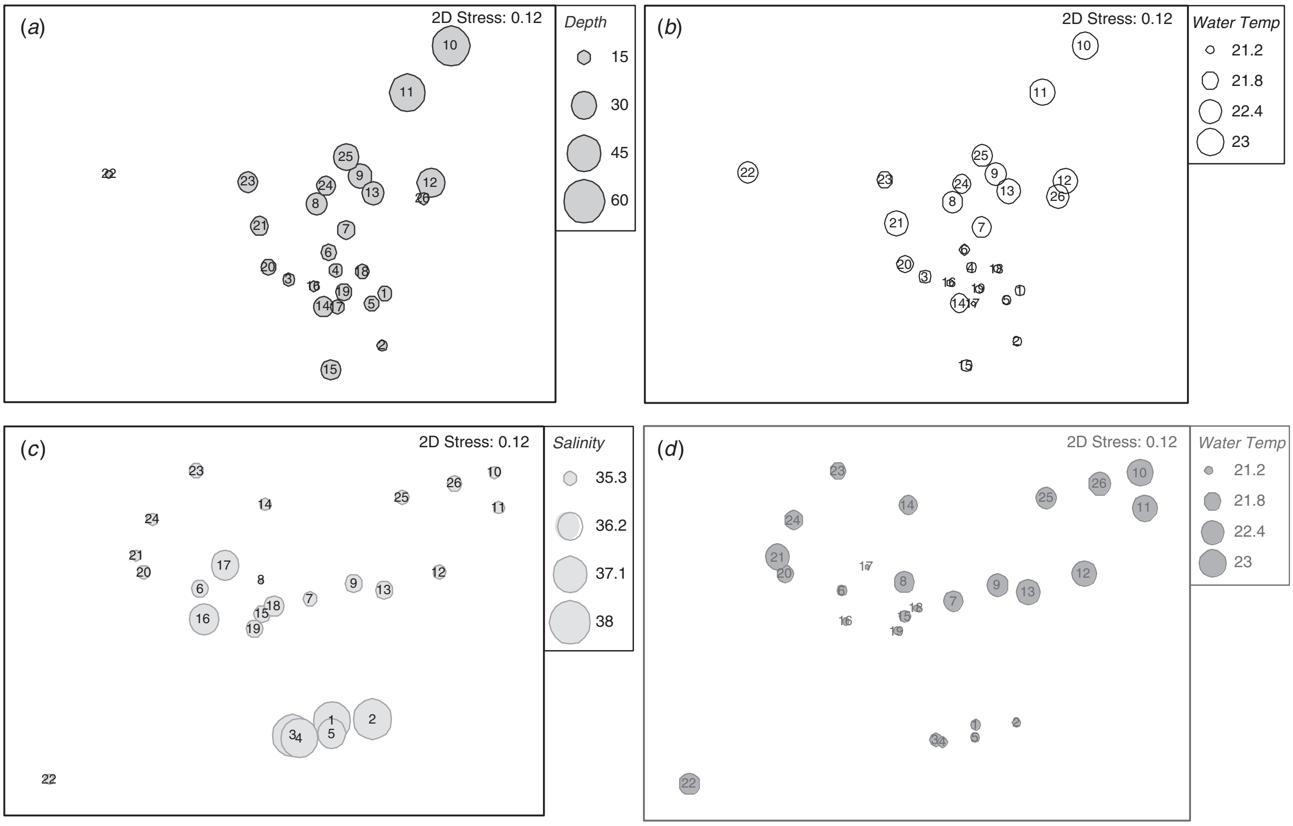

Fig. 5. (a) MDS of fish species assemblage at the 26 sites in Shark Bay with superimposed circles representing the water depth (m), (b) water temperature (°C), (c) MDS of invertebrate species assemblage at the 26 sites in Shark Bay with superimposed representing the salinity (ppt), (d) water temperature (°C).

first two being commercially harvested species. Abundances were similar in untrawled sites between November 2002 and November 2003 whereas trawled sites showed higher abundance in November 2003 compared with November 2002.

Depletion experiments

For all fish species combined, the catchability ($\hat{q}$) was 0.23 (s.e. ± 0.074) per night in February (Fig. 10*a*) and 0.06 (s.e. ± 0.022) per night in June (Fig. 10*b*). The low catchability overall in June was attributed to an increase in abundance over successive nights of the hair-finned leatherjacket (*P. choirocephalus*). When this species was removed from the analysis, the catchability for all the other 46 species recorded was 0.40 (s.e. ± 0.058). For all invertebrates $\hat{q}$ was 0.11 (s.e. ± 0.024) per night in February (Fig. 10*c*) with almost no decline observed in June. The low catchability in June was attributed to an increase in abundance over successive nights of a small scallop *Annachlamys flabellata* (Lamarck, 1819) and if this was removed from the dataset, $\hat{q}$ for all the other 76 invertebrate species recorded was 0.20 (s.e. ± 0.037) (Fig. 10*d*).

Over the four nights in February and June, respectively, 55% and 33% of fish species caught showed a declining trend in catches, with high variability in individual species catchability (Table 4). Of the remaining fish species, 21% in February and 11% in June showed catchability < 0.2, whereas 4% and 2% of fish species showed a positive trend in February and June respectively and the rest of the species were caught in insufficient numbers for analysis. For invertebrates, 31% and 50% caught showed a declining trend in February and June respectively in catches over four nights (Table 4). Of the remaining species, 23% and 4% showed catchability < 0.2 in February and June respectively, whereas 8% and 12% of invertebrate species showed a positive trend in February and June respectively with the rest of the species caught in insufficient numbers for analysis.

Individual species data

The spatial and temporal variation of some individual species that were sampled during depletion experiments were examined in detail. These included species with various levels of catchability and those that contributed most to declines in seasonal abundance. The selected species illustrate the variability in seasonal abundance and distribution of fish and invertebrate species (Figs 11–14).

The sea star *Luidia maculata* Müller & Trochel, 1842 and sponges (Porifera) had high catchability coefficients in the depletion experiments (Table 2). *Luidia maculata* was absent from northern and much of central Shark Bay for all sampling periods and was only present in low numbers in other parts of the bay (in both trawled and untrawled sites) except at site 2, (Fig. 11*a*) east of Cape Peron, where it was relatively abundant. This site is closed to trawling. Sponges were found in low

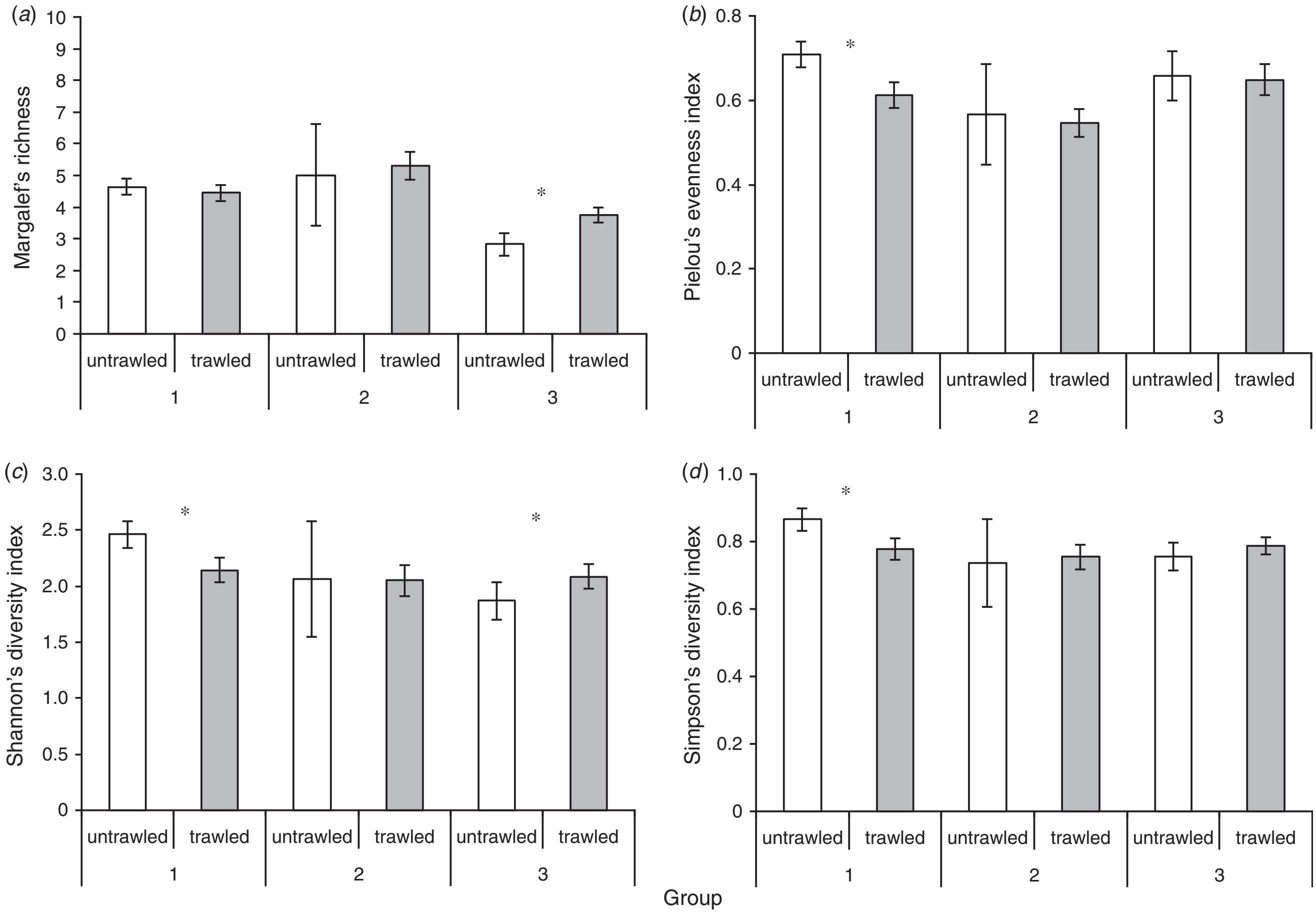

Fig. 6. Least-squares mean of indices with 95% confidence interval calculated for trawled and untrawled sties within groups identified from MDS of fish abundance in Shark Bay (*a*) Margalef's richness, (*b*) Pielou's eveness, (*c*) Shannon's diversity and (*d*) Simpson's diversity. * indicates significant differences between trawled and untrawled sites within the grouping.

abundance during at least one or two sampling periods at all survey sites, except for three sites, site 7 (moderate trawl intensity), site 2 (untrawled) and site 18 (low trawl intensity) (Fig. 11*b*). Seasonal trends in abundance could not be deduced due to the overall low sponge abundance.

All other invertebrate species had moderate catchability and individual species occurred in 62 to 100% of the sites sampled (Table 2). Cuttlefish (Sepiidae) were widespread throughout the bay and had a catchability coefficient of 0.3. Five species of cuttlefish were sampled during this study; however, Smith's cuttlefish (*Sepia smithi* Hoyle, 1885) was the most common. *Sepia smithi* was found throughout the bay and was the only cuttlefish species found in the northernmost sites, although it was only sampled there in February 2003. The Papuan cuttlefish (*Sepia papuensis* Hoyle, 1885) was the second most common cuttlefish species sampled and was found on at least one sampling period at all sites. No seasonal trends or differences in cuttlefish abundance were evident between trawled and untrawled sites (Fig. 11*c*).

Coral prawns include several different species, but *Metapenaeopsis crassissima* Racek & Dall, 1965 was generally the most abundant in Shark Bay. *Metapenaeopsis* was also the most abundant genus of invertebrates in Shark Bay and found at all survey sites (Fig. 11*d*). They were highly abundant in northern sites, where abundance generally declined throughout the year. In central Shark Bay they were absent at the start of the year but were generally found in the rest of the sampling periods. Much lower abundances were observed in the southern parts (both western and eastern regions, in trawled and untrawled sites) of Shark Bay but they were generally only sampled in these regions in the middle and end of the fishing season.

Several common fish species had high catchability (Table 1). The Western Australian butterfish (*Pentapodus vitta* Quoy & Gaimard, 1824) was among the ten most abundant trawl by-catch species in Shark Bay and was shown to have a high catchability coefficient. It was found at all sites except the six most northerly ones. It showed a marked decline in abundance over the trawl season in most sites except central Denham Sound and eastern gulf sites, where abundance increased in the middle of the season in adjacent trawled and untrawled sites (Fig. 12*a*).

The purple tuskfish, *Choerodon cephalotes* (Castelnau, 1875) was a species with high catchability although not especially abundant, but was widespread, occurring in all sites except the seven most northerly ones (Fig. 12*b*). It was most abundant in Denham Sound and east of Bernier Island in central Shark Bay. It showed a clear decline in seasonal abundance

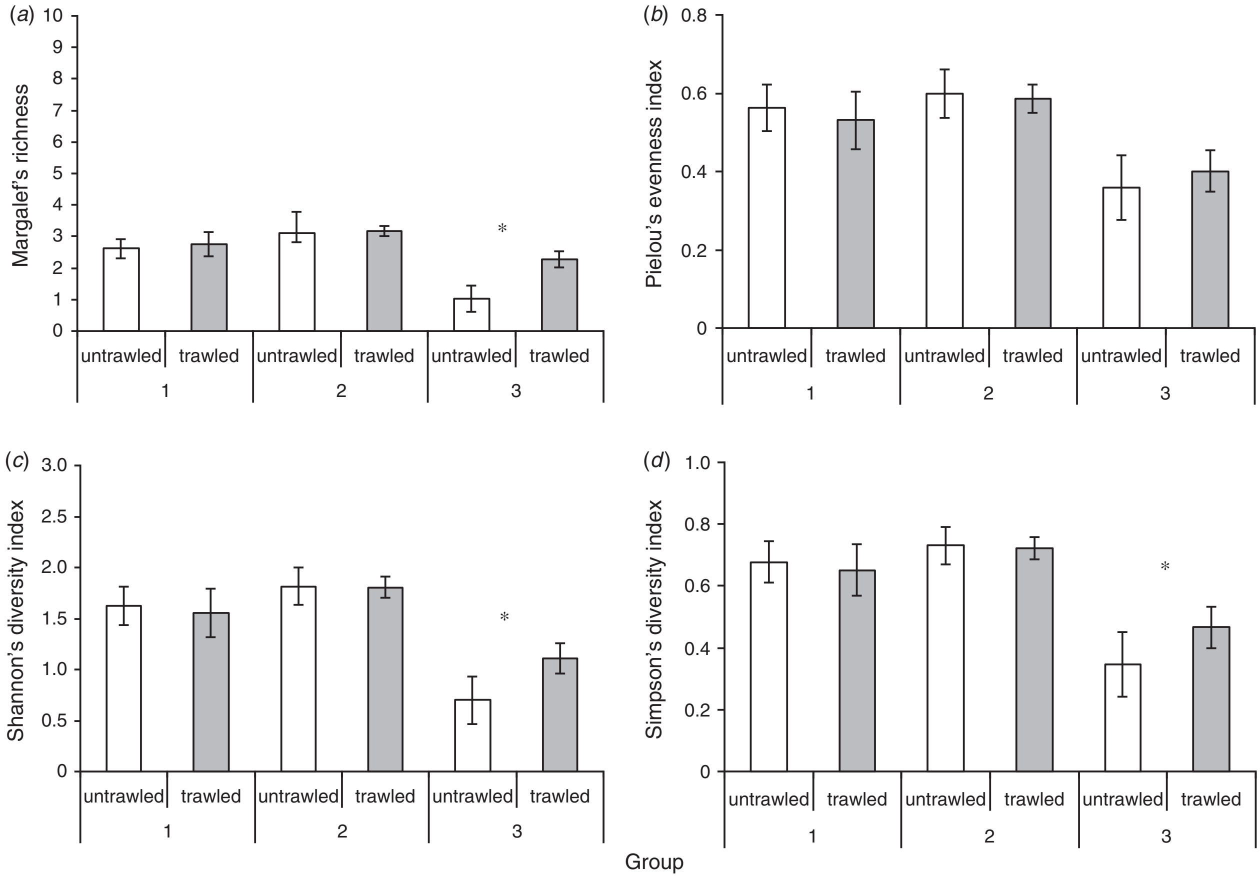

Fig. 7. Least-squares mean of indices with 95% confidence interval calculated for trawled and untrawled sites within groups identified from MDS of invertebrate abundance in Shark Bay (a) Margalef's richness, (b) Pielou's eveness, (c) Shannon's diversity and (d) Simpson's diversity. *indicates significant differences between trawled and untrawled sites within the grouping.

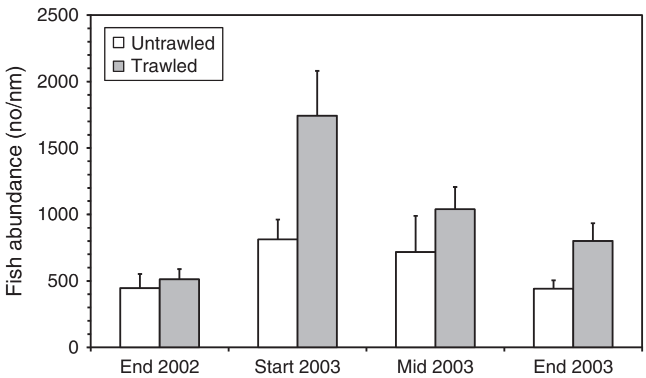

Fig. 8. Total fish abundance (no/nm + s.e.) in trawled and untrawled sites in Shark Bay over four seasons in 2002 and 2003.

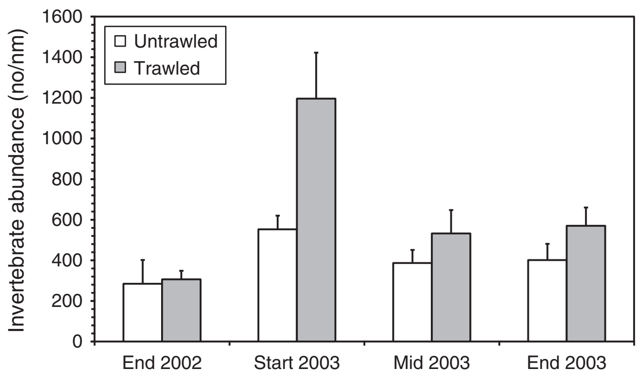

Fig. 9. Total invertebrate abundance (no/nm + s.e.) in trawled and untrawled sites in Shark Bay over four seasons in 2002 and 2003.

during 2003 at most sites but also showed variable abundance between the two years. The western striped grunter, *Pelates octolineatus* (Jenyns, 1814) also had high catchability and was only abundant in the southern gulfs of Shark Bay; it was rarely caught in the central sites and was completely absent from the northern sites (Fig. 12*c*). In the majority of sites it showed a clear decline in abundance over the trawl season, except at site 15 in Denham Sound where it was abundant in November 2002 but in much lower abundance for all sampling periods in 2003. In the eastern gulf, *P. octolineatus* was in higher abundance (in both trawled and untrawled sites) at the start of the fishing season and then was in much lower abundance the rest of the year. The fishnet lizardfish, *Synodus sageneus* Waite, 1905, also had a catchability coefficient around 0.5 but was only absent from the three most northerly sites (sites 10, 11 and 12, Fig. 12*d*). It was present in almost all seasons at all the other sites. It showed a decline in abundance in the central sites during the fishing season but no clear trends in the other sites.

The spiny-headed flounder, *Engyprosopon grandisquama* (Temminck & Schlegel, 1846) was one of the twenty most abundant trawl fish species, was shown to have moderate catchability (0.35) and was widely distributed throughout Shark Bay, being present at all sites in almost all seasons (Fig. 13*a*). It was most numerous in the central regions and, in the majority of sites, showed an increase in abundance by the end of the trawl season. The fanbelly leatherjacket, *M. chinensis*, was also a species with moderate catchability (Table 1) and was widespread in southern and eastern gulfs in both trawled and untrawled sites, lower in abundance in the central region and absent from the northern region (Fig. 13*b*). It showed the most

Table 3. Permanova results for fish and invertebrate species in Shark Bay biodiversity trawls

Only observations for 2003 were included in this analysis. Type 3 sum of squares have been presented. (*A*) Fish ($R^2 = 0.10$). (*B*) Invertebrates ($R^2 = 0.11$)

Source	d.f.	SS	MS	Pseudo-F	P(perm)	perms
A						
Trawled	1	17093	17093	9.04	<0.01	997
Season	2	21591	10795	5.71	<0.01	999
Trawled × season	2	5584	2792	1.48	0.07	999
Residuals	209	3.95E+05	1891			
B						
Trawled	1	8556	8556	3.88	<0.01	998
Season	2	43803	21902	9.94	<0.01	997
Trawled × season	2	6338	3169	1.43	0.12	999
Residuals	209	4.60E+05	2202			

marked decrease in abundance at the majority of sites during the trawl season of all the fish species examined in detail. At site 13 it was caught in large numbers at the start of the 2003 season but was absent from the two later 2003 season surveys.

Two fish species with low catchability were the western trumpeter whiting, *Sillago burrus* Richardson, 1842, and long-spine dragonet, *Pseudocalliurichthys goodladi* (Whitley, 1944), both different in their habits, with the whiting being benthic but quite mobile and feeding on small fishes and invertebrates and the dragonet being benthic and feeding on small invertebrates. *Sillago burrus* has a very similar distribution to that of the western striped grunter, except that there were low numbers present in some of the northerly sites and only at the start of the season. *S. burrus* also showed a similar declining trend in abundance throughout the trawl season in the southern areas, except for site 15, which also had a large increase mid-season (Fig. 13*c*). *Pseudocalliurichthys goodladi* was present at all sites except the most northerly site 10 (Fig. 13*d*). It was, however, in very low abundance over the whole northern region. In central sites it showed a decline in abundance over the trawl season, but in most southern and eastern gulf sites increased in abundance over the year.

Only a small proportion of invertebrate and fish species contributed to the observed declines in abundance during the trawl season. The crab, *P. rubromarginatus* was widespread and found at all the sites sampled and contributed to the apparent decline in invertebrate abundance between February and June 2003 where it had high abundances in the central and southern parts of Shark Bay in February and declined significantly in June (Fig. 14*a*). Three of the fish species (*U. asymmetricus, T. pallimaculatus* and *L. genivittatus*) that contributed to the general decline in fish abundance were all widespread (Fig. 14*b–d*); however, they all showed different annual and within-season trends. *Upeneus asymmetricus* was found at all sites in all early sampling periods except the most northern site

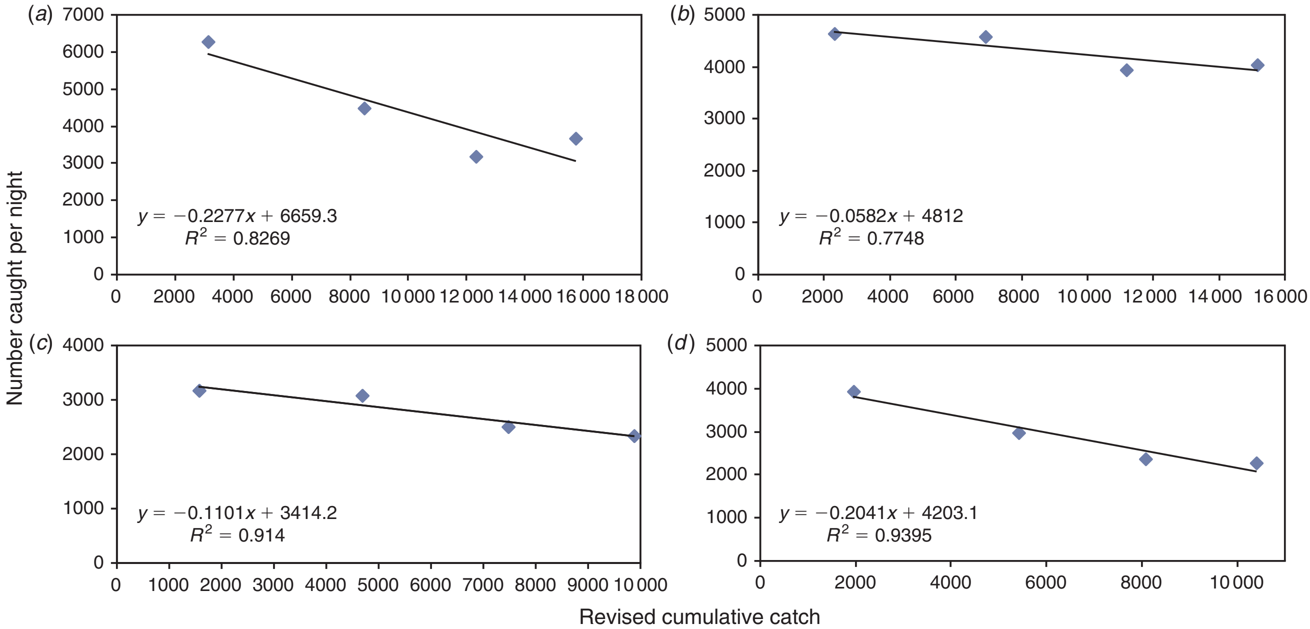

Fig. 10. Depletion estimates of catchability of total fish and invertebrate species over four nights of trawling in Denham Sound (*a*) fish in February, (*b*) fish in June, (*c*) invertebrates in February, (*d*) all invertebrates, other than *Annachlamys flabellata* in June.

and displayed either a declining abundance between February and November or a slight increase in numbers at a few sites (Fig. 14*a*). *Torquigener pallimaculatus* was found at all sites but was only found in high abundance in central regions and part of Denham Sound in February, followed by an overall decline (Fig. 14*c*). In south-eastern parts it was in very low abundance at the start of the year and increased during the year at both trawled and untrawled sites. *Lethrinus genivittatus* was found at most sites, but abundance varied greatly with high abundance only at 6 sites in central Shark Bay and the northern part of Denham Sound in 2003. It was, however, only found in two sites in November 2002, indicating a high annual variability in this species (Fig. 14*d*).

Table 4. Catchability (*q*) of fish and invertebrate species (±s.e.) for depletion experiments in February and June 2003 where depletion was evident for at least one experiment

NA – number of individuals too low for analysis

Common name	Species	February 2003	June 2003
Netted lizardfish	*Synodus sageneus*	0.706 ± 0.094	0.768 ± 0.098
Monocle bream	*Pentapodus vitta*	0.722 ± 0.257	1.307 ± 0.033
Trumpeter	*Pelates octolineatus*	0.561 ± 0.603	1.18 ± 0.158
Robust whiting	*Sillago robusta*	1.130 ± 0.164	0.913 ± 0.059
Bar tailed goatfish	*Upeneus tragula*	0.130 ± 0.089	0.908 ± 0.024
Orange spotted toadfish	*Torquigener pallimaculatus*	0.004 ± 0.019	1.020 ± 0.120
Threadfin emperor	*Lethrinus genivittatus*	NA	0.695 ± 0.028
Yellow-striped goatfish	*Parupeneus chrysopleuron*	NA	0.883 ± 0.182
Purple tuskfish	*Choerodon cephalotes*	NA	1.120 ± 0.090
Rusty flathead	*Inegocia japonica*	0.260 ± 0.095	0.363 ± 0.043
Spiny-headed flounder	*Engyprosopon grandisquama*	0.424 ± 0.130	0.418 ± 0.022
Fan-bellied leatherjacket	*Monacanthus chinensis*	0.204 ± 0.155	0.517 ± 0.152
Red-barred grubfish	*Parapercis nebulosa*	NA	0.397 ± 0.038
Multifilament stinkfish	*Repomucenus sublaevis*	NA	0.459 ± 0.077
Trumpeter whiting	*Sillago burrus*	0.140 ± 0.105	NA
Goodlad's stinkfish	*Pseudocalliurichthys goodladi*	NA	0.192 ± 0.061
Intermediate flounder	*Asterorhombus intermedius*	0.306 ± 0.113	0.032 ± 0.228
Seastar	*Luidia maculata*	NA	1.173 ± 0.253
Sponges	*Porifera*	NA	0.739 ± 0.102
Saucer scallop	*Amusium balloti*	0.532 ± 0.029	0.496 ± 0.071
Sea cucumber	*Colochirus crassus*	NA	0.513 ± 0.095
Brown tiger prawn	*Penaeus esculentus*	0.511 ± 0.066	0.124 ± 0.072
Cuttlefish	*Sepiidae*	0.480 ± 0.092	0.366 ± 0.046
Swimmer crab	*Portunus rubromarginatus*	0.121 ± 0.073	0.318 ± 0.069
Feather star	*Crinoidea*	NA	0.316 ± 0.105
Endeavour prawn	*Metapenaeus endeavouri*	0.256 ± 0.077	NA
Coral prawn	*Metapenaeopsis crassisima*	0.233 ± 0.098	0.109 ± 0.037
Stomatopod	*Squillidae*	NA	0.309 ± 0.193
Slipper lobster	*Scyllus martensii*	NA	0.247 ± 0.073
Sea slug	*Philine sp.*	0.018 ± 0.270	0.621 ± 0.126

Levels of trawl effort and fish abundance

Analysis of variance of overall Shark Bay fish family catch rates (square-root transformed) indicated a significant effect from previous trawl effort, $F_{3,460} = 4.50, P = 0.004$. Post-hoc tests for trawl effort indicated that low trawl effort (Trawl Effort Category 1) had significantly higher catch rates than the other levels of trawl effort including zero trawl effort. For this observed F-value the observed power of the ANOVA test at 5%, was 40% and at 10% was 47%.

Discussion

Shark Bay is an unusual embayment with limited freshwater run-off from the mainland and extensive shallow and inshore areas in the southern gulfs that have limited exchange with oceanic waters (Logan and Cebulski 1970). These geographical conditions result in hypersaline southern gulfs and large fluctuations in water temperature in shallow areas throughout the year. It is possible that environmental variables of water temperature, salinity and depth were more significant in determining faunal assemblages between sites than the level of trawl intensity. Depth and temperature had a 0.67 correlation with the fish species assemblage groups, whilst salinity and temperature had a 0.51 correlation with the invertebrate species assemblage groups, which may be due to their more limited mobility.

When individual sites were examined for environmental variables, salinity attributed to the highest variation observed for fish species with no significant contribution of whether the site was trawled or untrawled for any of the diversity indices examined. For invertebrates species, depth was the variable providing the highest % variation for any of the indices but there was some evidence that the Margalef's richness index had a significant variation associated with whether the site was trawled or untrawled.

Many of the individual species examined were absent or had very low abundance in the northernmost sites of Shark Bay, which had typically oceanic conditions and greater depths than the rest of the bay, and were shown to be in much higher abundance in the southern parts of Shark Bay. However, their distributions were often similar in both trawled and untrawled sites in these regions.

Results of this study substantially augment the understanding of the impacts of trawling on the Shark Bay ecosystem and in particular provides a detailed spatial and seasonal assessment of benthic communities including areas where no trawling occurs. The identification of distinct community groups with species diversity and abundance heavily influenced by environmental factors of salinity and depth is important. The latitudinal effects appear to exert a stronger influence on community structure than the effects of trawling, although for fish it was shown that the fishing impacts were detectable with moderate to high trawl intensities and that low trawl effort sites had the highest abundances. This lends support for the provision of areas closed to trawling in all systems to understand long-term effects of trawling on the ecosystem. The depletion experiments clearly indicated that some species are much more vulnerable to trawling, particularly sessile ones or species with limited mobility, but direct trawl impact on many of these species was difficult to detect. It has been previously observed that natural environmental variability is often greater than fishing-induced changes (Jones 2000), further masking the effects of trawl activity. Even so, major differences were not detectable between those sites that have been closed to trawling for decades and those sites that are fished. Similar results have been found in other trawl impact studies (Simpson and Watling 2006, Lindegarth *et al.* 2000, Kenchington *et al.* 2001).

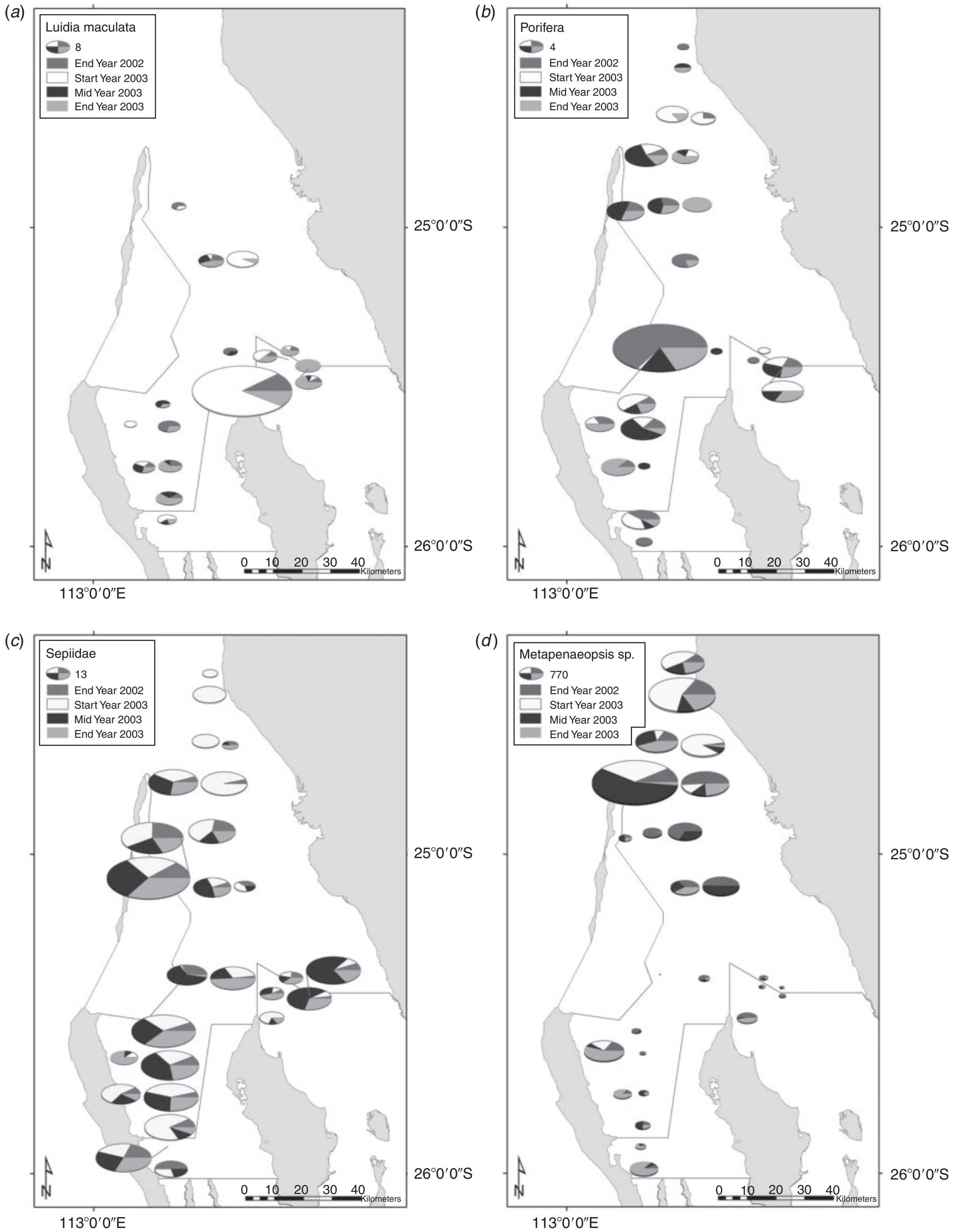

Fig. 11. Seasonal and spatial distribution of key invertebrate species sampled during depletion experiments in February and June 2003 (*a*) *Luidia maculata*, (*b*) Porifera, (*c*) Sepiidae and (*d*) *Metapenaeopsis* spp.

Commercial trawling has been occurring in Shark Bay since 1963. Broad scale and long-term changes in community structure cannot be scientifically tested in Shark Bay given studies were not undertaken before commencement of trawling more than 50 years ago. It has been observed elsewhere that high levels of trawling may not only decrease the complexity of the habitat and biodiversity of the fauna, but also enhance the abundance of opportunistic species including prey species that

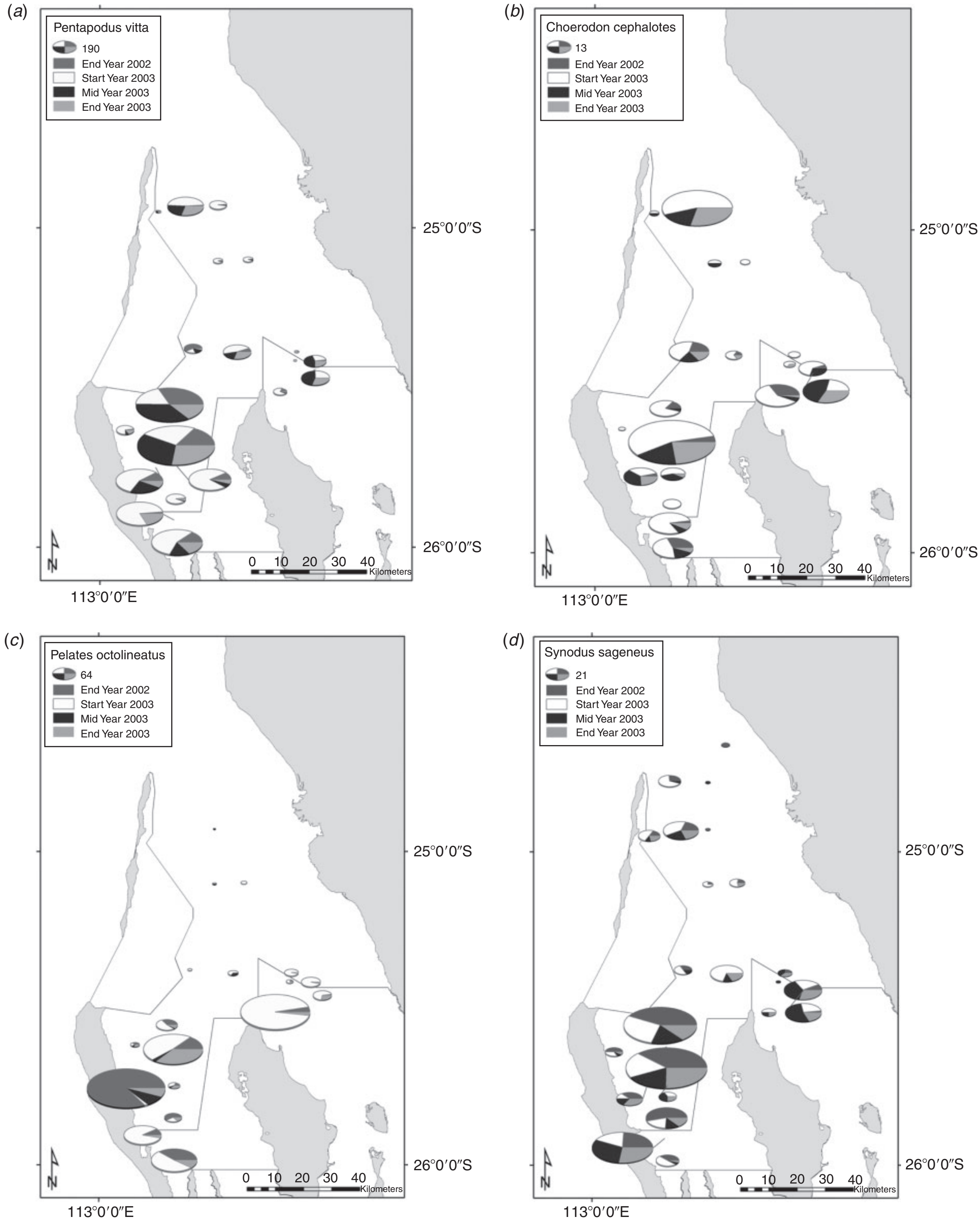

Fig. 12. Seasonal and spatial distribution of key fish species sampled during depletion experiments in February and June 2003 (*a*) *Pentapodus vitta,* (*b*) *Choerodon cephalotes*, (*c*) *Pelates octolineatus* and (*d*) *Synodus sageneus.*

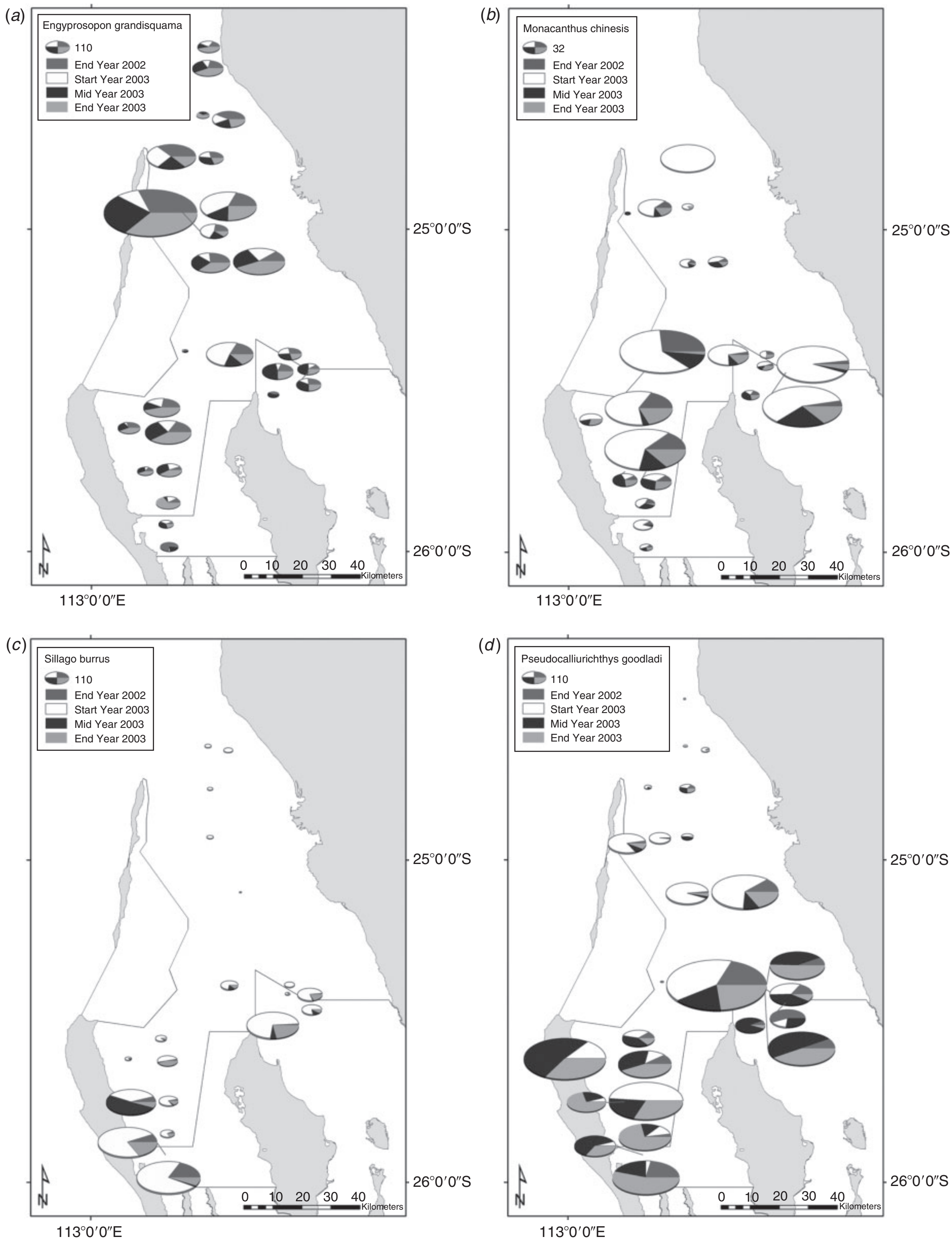

Fig. 13. Seasonal and spatial distribution of key fish species sampled during depletion experiments in February and June 2003 (*a*) *Engyprosopon grandisquama,* (*b*) *Monacanthus chinensis*, (*c*) *Sillago burrus* and (*d*) *Pseudocalliurichthys goodladi.*

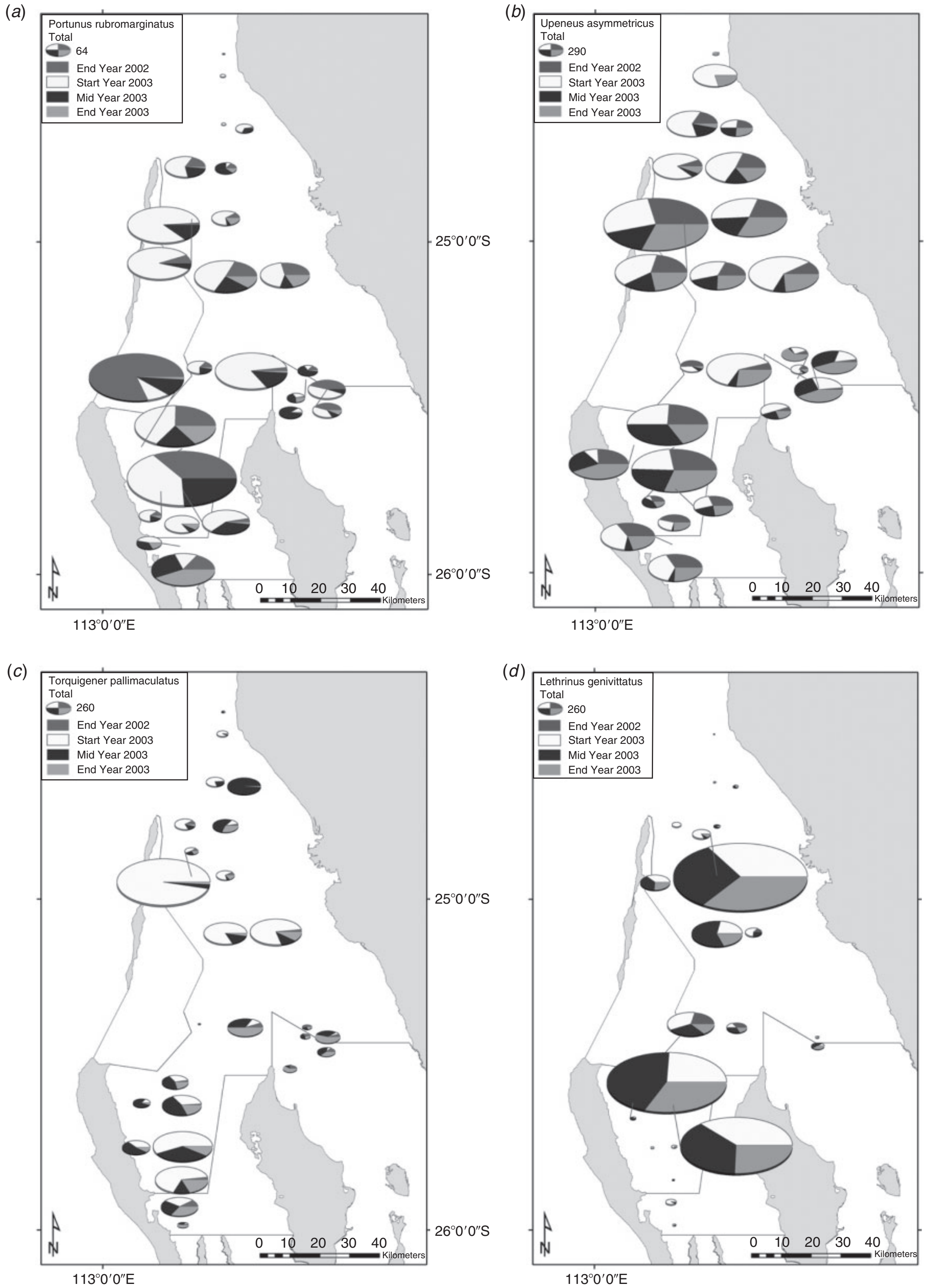

Fig. 14. Seasonal and spatial distribution of key fish species sampled during depletion experiments in February and June 2003. (*a*) *Portunus rubromarginatus*, (*b*) *Upeneus asymmetricus*, (*c*) *Torquigener pallimaculatus* and (*d*) *Lethrinus genivittatus.*

are important in the diet of some commercial species (Engel and Kvitek, 1998, Auster *et al.* 1996, Hinz *et al.* 2009). Many of these studies have been undertaken in areas where trawling effort has been significantly more intensive than that in Shark Bay, which has had limited entry since the onset of fishing and large areas closed to trawling.

Despite the large number of faunal species recorded in this survey, only a small proportion were abundant and widely distributed in Shark Bay. Twenty of the most abundant fish and invertebrate species contributed 60 to 80% of the total fish and invertebrates sampled and caught in 60 to 80% of the sites studied. Thirty percent of fish and 48% of invertebrate species sampled were uncommon (found in one or two sites only) and these species are therefore not considered to be useful indicators of biodiversity due their rarity.

There was a significant seasonal decline in fish abundance from the period before the start of the fishing season in February to the end of the season in November. This decline was primarily attributed to a reduction in abundance of five species *L. genivittatus, P.choirocephalus, P.quadrilineatus, T. pallimaculatus* and *U. asymmetricus* and this occurred in both trawled and untrawled sites, which possibly reflects a seasonal variation in abundance and/or movement between trawled and untrawled areas. Invertebrate species abundance was observed to only decline significantly between February and June in both trawled and untrawled sites. This was attributed to the very abundant species *A. balloti, P. latisulcatus, P. rubromarginatus* and *H. pallida* the first two being commercially harvested species. As with the fish species, these four dominant invertebrate species drive the abundance patterns.

Diversity measures were compared to further understand trawl impacts, but no consistent variation in indices were observed in groups of sites within assemblage groups nor were the differences attributable to whether a site was trawled or not. Such baseline information indicates how variable species richness and evenness can be at all sites in all seasons and between years. This indicates that species abundances, richness, diversity and evenness are likely driven by a complex suite of factors, in addition to depletion from trawling and environmental gradients.

Depletion experiments highlighted temporal and species variation in catchability by trawl gear. Some species were relatively susceptible to the trawl gear, depending on their mobility, patterns of movement, size, physical form, burying ability, feeding mode and whether they are attracted to disturbed substrates. Susceptible species were considered to have catchability coefficients greater than 0.6. These were the invertebrates *L. maculata* and the phylum Porifera and the fish *P. octolineatus, Parupeneus chrysopleuron* (Temminck & Schlegel, 1843), *L. genivittatus, S. sageneus, P. vitta, C. cephalotes* and *S. robusta.* Despite a clear abundance decline in some species during the fishing season, no obvious impact from trawling could be discerned from abundance and distribution patterns of the species examined in detail, even in those with high catchability coefficients. It was, however, observed that all species recorded on the trawl grounds were also present to some degree in untrawled (closed) areas.

Other groups of species such as serranids, labrids, gobiids, gastropod molluscs and some of the threatened species of elasmobranchs and syngnathids were poorly sampled by trawl gear and their abundance or impact of trawling on them could not be quantified by this method.

In order to manage impacts of fishing, particularly trawling in Shark Bay, the approach adopted by the Department of Fisheries in Western Australia is to acknowledge that trawling has a level of impact on trawl by-catch species and habitats, (as supported by this study), and therefore limit the area where trawling can occur to an acceptable percentage of the trawlable habitat to at least less than 50%. In Shark Bay only 20–40% of fishery area is open to trawling (Sporer *et al.* 2012, Kangas *et al.* 2006). The management of trawl areas using permanent and seasonal closures within Shark Bay ensures that the more vulnerable species are protected, as the majority of species occur in both trawled and untrawled areas. Such limits on trawling ensure that sufficient refuge areas are available within suitable habitat for the vulnerable species and that assemblages potentially affected by trawling are not put at risk by these fishing activities. Individuals that live outside the trawl grounds are not exposed directly to trawling and they can also provide larval recruits to fished areas (Hill *et al.* 2002). Consequently ongoing management mainly requires that the areas trawled be maintained within the defined boundaries and monitored using satellite monitoring systems (VMS). It has been highlighted during the 50 year history of trawl fisheries in Shark Bay that large area closures also protect recruitment of prawns and therefore is highly beneficial to the fishery and supported by industry.

However, monitoring of longer-term changes in faunal assemblages as a consequence of fishing and climate change will be of interest in the region, particularly given some recent extreme heatwave events that have affected recruitment and caused significant mortality of key commercial species (*A. balloti* and *Portunus armatus* (Milne-Edwards, 1861)) in Shark Bay (Pearce *et al.* 2011, Pearce and Feng 2013) whilst the fate of other trawl by-catch species is unknown. Species which have a moderate to high catchability and those that are generally widespread (found in >70% of sites sampled) are good candidate indicator species for trend analyses. For Shark Bay this could include the fish species *Inegocia japonica* (Tilesius, 1812), *P. nebulosa, E. grandisquama, M. chinensis, S. sageneus, P. vitta, C. cephalotes, S. robusta, P.octolineatus* and *L. genivittatus*. These ten species represented, on average 19.6% (s.e. 2.3) of the total fish abundance. Species with low catchability or high mobility are less reliable as indicators as catch rates will not represent actual abundance. For invertebrate species, the only suitable indicator species were the group Porifera (found in 50% of sites) and the sea star *L. maculata* as all the other invertebrate species that displayed medium to high catchability are commercially targeted species (or secondary species) or schooling, mobile species such as the cephalopods. Burridge *et al.* (2003) found gastropods to be highly susceptible to trawling but this group were uncommon in Shark Bay trawl catches.

If future monitoring indicates a need to reduce trawl impacts on biodiversity in Shark Bay this may be achieved by extending the use of current management tools. These include area and time closures, targeted harvesting strategies to optimise expenditure of effort, a reduction of overall fishing effort (reduction of boats or time and/or area) to optimise economic yield and use of mechanical or other devices such as BRDs and hoppers. These management tools have already been used extensively in the prawn and scallop fisheries in Western Australia to reduce the time and cost of fishing, as well as minimising the area of fishing by having extensive permanently closed areas and areas that are opened and closed according to prawn/scallop size and catch rates.

Cost-effective sampling methods are the only solution in the long term. Monitoring could be undertaken every 4 to 5 years (to cover ENSO cycles that occur every 3–7 years) and if significant changes in abundance or shifts in diversity measures are observed, then the sampling should be repeated the following year. Trends in the spatial distribution of effort can easily be monitored annually to determine if there is a significant shift in effort distribution. Stobutzki *et al.* (2000) found that if they sampled 10% of a trawl catch it generally represented ~50% of the species caught because many rare or uncommon species occur in low numbers in trawl by-catch. Consequently sub-sampling and a focus on indicator species (as above) would be adequate for long-term monitoring. As seasonal variability is evident in total by-catch abundance, any repeated sampling needs to be undertaken at a similar time of year.

Acknowledgments

This project was funded by the Fisheries Research and Development Corporation FRDC 2002/038 and the Shark Bay prawn, Exmouth Gulf prawn and Shark Bay scallop industries. We would like to thank the Steering Committee members, Jim Penn, Steven Hood, Graeme Stewart, Hamish Ch'ng, Fred Wells and Nic Dunlop for their contribution, guidance and interest in the project. Thanks to Nick Caputi for invaluable comments on this paper. Thanks to the RV Naturaliste crew; Theo Berden, Mark Baxter, Kim Hillier, Tim Shepherd and Shaun O'Hara for their enthusiasm and commitment during the project. Research and technical staff were, Phil Unsworth, Gareth Parry, Josh Brown, Jim Penn, Gary Jackson, Mike Moran and Heidi Greif. Statistical advice and assistance was provided by Eva Lai, Adrian Thomson and Ian Wright and figures were made by Sharon Wilkin. We are grateful to the staff of the WA Museum; Corey Whisson, Shirley Slack-Smith, Melissa Titelius, Jenny Hutchins, Glenn Moore and Jane Fromont, for both field assistance and identifications. Loisette Marsh, Barry Hutchins, Dianne Jones, Mark Salotti and Hugh Morrison from the WA Museum assisted with species identifications. Thank you to the volunteers, Maryanne Evetts, Marie Shanks and Mike Travers who assisted with fieldwork.

References

Addison, J. T., Lawler, A. R., and Nichlson, M. D. (2003). Adjusting for variable catchability of brown shrimps (*Crangon crangon*) in research surveys. *Fisheries Research* **65**, 285–294. doi:10.1016/J.FISHRES.2003.09.020

Anderson, M. J. (2001). Permutation tests for univariate or multivariate analysis of variance and regression. *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 626–639. doi:10.1139/F01-004

Andrew, N. L., and Pepperell, J. G. (1992). The bycatch of shrimp trawl fisheries. *Oceanography and Marine Biology - an Annual Review* **30**, 527–565.

Auster, P. J., Maltesta, R. J., Langton, R. W., Watling, L., Valentine, P. C., Donaldson, C. L. S., Langton, E. W., Shepard, A. N., and Babb, I. G. (1996). The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (Northwest Atlantic): implications for conservation of fish populations. *Reviews in Fisheries Science* **4**, 185–202. doi:10.1080/10641269609388584

Bishop, J. M., Ye, Y., Alsaffar, A. H., AlFoudari, H. M., and Jazzaf, S. (2008). Diurnal and nocturnal catchability of Kuwait's commercial shrimps. *Fisheries Research* **94**, 58–72. doi:10.1016/J.FISHRES.2008.06.020

Broadhurst, M. K., Kennelly, S. J., and Barker, D. T. (1997). Simulated escape of juvenile sand whiting *(Sillago ciliata,* Cuvier) through square-meshes: effect on scale-loss and survival. *Fisheries Research* **32**, 51–60. doi:10.1016/S0165-7836(97)00037-4

Broadhurst, M. K., Kangas, M. I., Damiano, C., Bickford, S. A., and Kennelly, S. J. (2002). Using composite square-mesh panels and the Nordmore-grid to reduce bycatch in the Shark Bay prawn trawl fishery, Western Australia. *Fisheries Research* **58**, 349–365. doi:10.1016/S0165-7836(01)00390-3

Burridge, C. Y., Pitcher, C. R., Wassenberg, T. J., Poiner, I. R., and Hill, B. J. (2003). Measurement of the rate of depletion of benthic fauna by prawn (shrimp) otter trawls: an experiment in the Great Barrier Reef, Australia. *Fisheries Research* **60**, 237–253. doi:10.1016/S0165-7836(02)00179-0

Clarke, K. R., and Ainsworth, M. (1993). A method of linking multivariate community structure to environmental variables. *Ecology Progress Series* **92**, 205–219. doi:10.3354/MEPS092205

Clarke, K. R., and Warwick, R. M. (2001). 'Changes in Marine Communities: an Approach to Statistical Analysis and Interpretation.' 2nd edn. (Primer-E: Plymouth, UK.)

Currie, D. R., Dixon, C. D., Roberts, S. D., Hooper, G. E., Sorokin, S. J., and Ward, T. M. (2011). Relative importance of environmental gradients and historical trawling effort in determining the composition and distribution of benthic macro-biota in a large inverse estuary. *Fisheries Research* **107**, 184–195. doi:10.1016/J.FISHRES.2010.11.003

Department of Fisheries (2000) Fisheries Environmental Management Review No. 1 Department of Fisheries, Western Australia.

Engel, J., and Kvitek, R. (1998). Effects of Otter Trawling on a Benthic Community in Monterey bay National Marine Sanctuary. *Conservation Biology* **12**, 1204–1214. doi:10.1046/J.1523-1739.1998.0120061204.X

Fletcher, W. J., and Santoro, K. (2011) State of the Fisheries and Aquatic Resources Report 2010/11, Department of Fisheries, Western Australia.

Gordon, D. C., Schwinghamer, P., Rowell, T. W., Prena, J., Gilkinson, K., Vass, W. P., and McKeown, D. L. (1997). Studies in Canada on the impact of mobile fishing gear on benthic habitats and communities. In 'Proceedings of the Conference on Effects of Fishing Gear on the Sea Floor of New England. Northeastern University, 30 May 1997'.

Hall, S. J. (1999). 'The Effects of Fishing on Marine Ecosystems and Communities.' (Blackwell Science: UK.)

Hill, B. J., Haywood, M., Venables, B., Gordon, S., Condie, S., Ellis, N. R., Tyre, A., Vance, D., Dunn, J., Mansbridge, J., Moeseneder, C., Bustamante, R., and Pantus, F. (2002). Surrogates 1: predictors, impacts, management and conservation of the benthic biodiversity of the Northern Prawn Fishery. FRDC Project no. 2000/160. Cleveland, Qld.: CSIRO Marine Research; Fisheries Research & Development Corporation.

Hinz, H., Prieto, V., and Kaiser, M. J. (2009). Trawl disturbance on benthic communities: chronic effects and experimental predictions. *Ecological Applications* **19**, 761–773. doi:10.1890/08-0351.1

Horn, H. S. (1966). Measurement of "overlap" in comparative ecological studies. *American Naturalist* **100**, 419–424. doi:10.1086/282436

Joll, L. M., and Caputi, N. (1995*a*). Geographic variation in the reproductive cycle of the saucer scallop, *Amusium balloti* (Bernardi, 1861) (Mollusca: Pectinidae), along the Western Australian coast. *Marine and Freshwater Research* **46**, 779–792. doi:10.1071/MF9950779

Joll, L. M., and Caputi, N. (1995*b*). Environmental influences on recruitment in the saucer scallop (*Amusium balloti*) fishery of Shark Bay, Western Australia. *ICES Marine Science Symposia* **199**, 47–53.

Joll, L. M., and Penn, J. W. (1990). The application of high-resolution navigation systems to Leslie-DeLury depletion experiments for the measurements of trawl efficiency under opine-sea conditions. *Fisheries Research* **9**, 41–55. doi:10.1016/0165-7836(90)90039-X

Jones, M. (2000). Fisheries and the Environment. pp. 53–73. In: Caton, A. and McLoughlin, K. (Eds.) Fishery Status Report 1999: Resource Assessments of Australian Commonwealth Fisheries. Bureau of Rural Sciences, Canberra.

Kangas, M., and Thomson, A. (2004). Implementation and assessment of bycatch reduction devices in the Shark Bay and Exmouth Gulf trawl fisheries. Final report FRDC 2000/189.

Kangas, M., McCrea, J., Fletcher, W., and Sporer, E. And Weir, V. (2006) Shark Bay Prawn Fishery, ESD Report Series No. 3. Department of Fisheries WA.

Kangas, M. I., Morrison, S., Unsworth, P., Lai, E., Wright, I., and Thomson, A. (2007). Development of biodiversity and habitat monitoring systems for key trawl fisheries in Western Australia. Final FRDC Report 2002/038. *Fisheries Research Report* 160.

Kenchington, E. R., Prena, J., Gilkinson, K. D., Gordon, D. C., Jr, MacIsaac, K., Bourbonnais, C., Shwinghamer, P. J., Rowell, T. W., McKeown, D. L., and Vass, W. P. (2001). Effects of experimental otter trawling on the macrofauna of a sandy bottom ecosystem on the Grand Banks of Newfoundland. *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 1043–1057. doi:10.1139/F01-053

Kendrick, G. A., Fourqurean, J. W., Fraser, M. W., Heithaus, M. R., Jackson, G., Friedman, K., and Hallac, D. (2012). Science behind management of Shark Bay and Florida Bay, two P-limited subtropical systems with different climatology and human pressures. *Marine and Freshwater Research* **63**, 941–951. doi:10.1071/MF12280

Kirkman, H., and Walker, D. I. (1989). Regional studies – Western Australian seagrass. In 'Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region'. (Eds A. W. D. Larkum, A. J. McComb and S. A. Shepherd.) pp. 157–181. (Aquatic Studies 2.) (Elsevier: Amsterdam.)

Krebs, C. J. (1999). 'Ecological Methodology.' 2nd edn. (Addison Wesley: Menlo Park, CA.)

Lindegarth, M., Valentinsson, D., Hansson, M., and Ulmestrand, M. (2000). Effects of trawling disturbances on temporal and spatial structure of benthic soft-sediment assemblages in Gullmarsfjorden, Sweden. *ICES Journal of Marine Science* **57**, 1369–1376. doi:10.1006/JMSC.2000.0903

Logan, B. W., and Cebulski, D. E. (1970). Sedimentary Environments of Shark Bay, Western Australia. In 'Carbonate Sedimentation and Environments, Shark Bay, Western Australia'. The American Association of Petroleum Geologists, Memoir No. 13.

Logan, B. W., Read, J. F., Hagan, G. M., Hoffman, P., Brown, R. G., Woods, P. J., and Gebelein, C. D. (1974). Evolution and Diagenesis of Quaternary Carbonate Sequneces, Shark Bay, Western Australia. The American Association of Petroleum Geologists, Memoir No. 22.

Margalef, D. R. (1958). Information theory in ecology. *General Systems* **3**, 36–71.

McKeown, D. L., and Gordon, D. C. (1997). Grand Banks otter trawling impact experiment: II. Navigation procedures and results. *Canadian Technical Report of Fisheries and Aquatic Sciences* **2159**, 1–79.

Montgomery, S. S., Barchia, I. M., and Walsh, C. T. (2012). Estimating rates of mortality in stocks of *Metapenaus macleayi* in estuaries of eastern Australia. *Fisheries Research* **113**, 55–67. doi:10.1016/J.FISHRES.2011.09.003

Mueller, U., Kangas, M., Sporer, E., and Caputi, N. (2012). Variability in the spatial and temporal distribution of the saucer scallop *Amusium balloti* in Shark Bay – management implications. *Marine and Freshwater Research* **63**, 1152–1162. doi:10.1071/MF12051

Ogle, D. (2011). fishR Vignette – Depletion Methods for Estimating Abundance. Available from http://fshr.wordpress.com/vignettes/

Pearce, A. F., and Feng, M. (2013). The rise and fall of the "marine heat wave" off Western Australia during the summer of 2010/2011. *Journal of Marine Systems* **111–112**, 139–156. doi:10.1016/J.JMARSYS.2012.10.009

Pearce, A., Lenanton, R., Jackson, G., Moore, J., Feng, M., and Gaughan, D. (2011). The "marine heat wave" off Western Australia during the summer of 2010/11. Research Report 222, Department of Fisheries, Western Australia.

Penn, J. W. (1984). The behaviour and catchability of some commercially exploited penaeids and their relationship to stock and recruitment. In 'Penaeid Shrimps - Their Biology and Management'. (Eds J. A. Gulland and B. J. Rothschild.) pp. 173–186. (Fishing New Books: London.)

Penn, J. W., and Caputi, N. (1986). Spawning stock-recruitment relationships and environmental influences on the tiger prawn *(Penaeus esculentus)* fishery in Exmouth Gulf, Western Australia. *Australian Journal of Marine and Freshwater Research* **37**, 491–505. doi:10.1071/MF9860491

Pielou, E. C. (1975). 'Ecological Diversity.' (Wiley: New York.)

Pitcher, C. R., Poiner, I. R., Hill, B. J., and Burridge, C. T. (2000). Implications of the effects of trawling on sessile mega-zoobenthos on a tropical shelf in northeastern Australia. *ICES Journal of Marine Science* **57**, 1359–1368. doi:10.1006/JMSC.2000.0911

Playford, P. E. (1990). Geology of the Shark Bay area, Western Australia. In 'Research in Shark Bay. Report of the France-Australe Bicentenary Expedition Committee'. (Eds P. F. Berry, S. D. Bradshaw and B. R. Wilson.) pp. 13–31. (Western Australian Museum: Perth.)

Poiner, I., Glaister, J., Pitcher, R., Burridge, C., Wassenberg, T., Gribble, N., Hill, B., Blaber, S., Milton, D., Brewer, D., and Ellis, N. (1998). Environmental effects of prawn trawling in the Far Northern Section of the Great Barrier Reef: 1991–1996. Final Report to Great Barrier Reef Marine Park Authority and Fisheries Research and Development Corporation.

Saila, S. A. (1983). Importance and assessment of discards in commercial fisheries. *FAO Fisheries Circular* 765Z.

Simpson, E. H. (1949). Measurement of diversity. *Nature* **163**, 688. doi:10.1038/163688A0

Simpson, A. W., and Watling, L. (2006). An investigation of the cumulative impacts of shrimp trawling on mud-bottom fishing grounds in the Gulf of Maine: effects on habitat and macrofaunal community structure. *ICES Journal of Marine Science* **63**, 1616–1630. doi:10.1016/J.ICESJMS.2006.07.008

Sporer, E., Kangas, M., Brown, S., and Pickles, L. (2012) Shark Bay Prawn and Scallop Managed Fishery status report. In 'Status Reports of the Fisheries and Aquatic Resource of Western Australia 2011/12: the State of the Fisheries'. (Eds W. J. Fletcher and K. Santoro.) pp. 130–139. (Department of Fisheries Western Australia: Perth.)

Stewart-Oaten, A., Murdoch, W. M., and Parker, K. R. (1986). Environmental impact assessment: "pseudoreplication" in time? *Ecology* **67**, 929–940. doi:10.2307/1939815

Stobutzki, I., Blaber, S., Brewer, D., Fry, G., Heales, D., Miller, M., Milton, D., Salini, J., van der Velde, T., Wassenberg, T., Jones, P., You-Gang, W., Dredge, M., Courtney, T., Chilcott, K., and Eayrs, S. (2000). Ecological sustainability of bycatch and biodiversity in prawn trawl fisheries. Final Report to Fisheries Research and Development Corporation.

Stobutzki, I., Miller, M., and Brewer, D. (2001*a*). Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. *Environmental Conservation* **28**(2), 1–15. doi:10.1017/S0376892901000170

Stobutzki, I. C., Miller, M. J., Jones, P., and Salini, J. P. (2001*b*). Bycatch diversity and variation in a tropical Australian penaeid fishery; the implications for monitoring. *Fisheries Research* **53**, 283–301. doi:10.1016/S0165-7836(00)00273-3

Tonks, M. L., Griffiths, S. P., Heales, D. S., Brewer, D. T., and Dell, Q. (2008). Species composition and temporal variation of prawn trawl bycatch in the Joseph Bonaparte Gulf, northwestern Australia. *Fisheries Research* **89**, 276–293. doi:10.1016/J.FISHRES.2007.09.007

Underwood, A. J. (1993). The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. *Australian Journal of Ecology* **18**, 99–116. doi:10.1111/J.1442-9993.1993.TB00437.X

Walker, D. I. (1989) Regional studies - seagrass in Shark Bay, the foundations of an ecosystem. In 'Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region'. (Eds A. W. D. Larkum, A. J. McComb and S. A. Shepherd.) pp. 182–210. (Aquatic Studies 2.) (Elsevier: Amsterdam.)

Walker, D. I. (1990) Seagrass in Shark Bay, Western Australia. In 'Research in Shark Bay: Report of the France-Australe Bicentenary Expedition Committee'. (Eds P. F. Berry, S. D. Bradshaw and B. R. Wilson.) pp. 101–106. (Western Australian Museum: Perth.)

Walker, D. I., and Prince, R. I. T. (1987). Distribution and biogeography of seagrass species on the north-west coast of Australia. *Aquatic Botany* **29**, 19–32. doi:10.1016/0304-3770(87)90026-X

Wassenberg, T. J., Dew, G., and Cook, S. D. (2002). The impact of fish trawls on megabenthos (sponges) on the northwest shelf of Australia. *Fisheries Research* **58**, 141–151. doi:10.1016/S0165-7836(01)00382-4

Yousif, A. (2003). Diel variability of size and catch rate of three fish species and three penaeid prawns in the NW Red Sea trawl fishery. *Fisheries Research* **63**, 265–274. doi:10.1016/S0165-7836(03)00071-7