

Marine introductions in the Shark Bay World Heritage Property, Western Australia: a preliminary assessment

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ABSTRACT

The presence and impacts of non-indigenous species (NIS) in marine areas of high conservation or World Heritage significance have rarely been examined. Case studies worldwide suggest that the potential exists for the introduction of NIS to significantly impact conservation values in regions conserved for the uniqueness and diversity of native assemblages. In this study, a preliminary investigation was conducted to provide information essential for managing marine introductions in the Shark Bay World Heritage Property. A focused fouling plate survey sampled a total of 112 encrusting taxa, of which 10 (11.2%) were classified as introduced and 10 others as cryptogenic. Eight introduced bryozoans: *Aetea anguina* (Linnaeus, 1758), *Bugula neritina* (Linnaeus, 1758), *Bugula stolonifera* Ryland, 1960, *Conopeum seurati* (Canu, 1928), *Savignyella lafontii* (Audouin, 1826), *Schizoporella errata* (Waters, 1878), *Watersipora subtorquata* (d'Orbigny, 1842) and *Zoobotryon verticellatum* della Chiaje, 1828; one tunicate, *Styela plicata* Lesueur, 1823; and an introduced hydroid, *Obelia dichotoma* (Linnaeus, 1758) were frequent, and in some cases dominant, components of encrusting communities. Of the 20 most frequently occurring species detected in the Bay, four were introduced and of the 20 species with highest average percent cover per plate, six were introduced. At one site, space occupation by NIS averaged $71.6\% \pm 7.4$ of plate live cover. Space occupation by an individual NIS was as high as 62.4% of plate area (mean $7.82\% \pm 1.8$). NIS were detected at sites lacking commercial traffic and ballast water discharge and isolated by distance and physical environment, suggesting that hull fouling of recreational craft may be the most important vector in the region. Seventy-five percent of NIS detected in Shark Bay are established in Australian ports to the south of Shark Bay, while 33% are established to the north, tentatively implicating temperate affinity NIS and the movement of vessels from Australian ports south of Shark Bay as a greater risk to the region.

Keywords

Biological invasions, fouling community, hull fouling, non-indigenous species (NIS), tropical/temperate affinity.

INTRODUCTION

Non-indigenous species (NIS) have direct and indirect impacts on native diversity at local scales and also contribute to regional homogenization of communities (Ruiz *et al.*, 1997; McKinney, 1998; Lavoie *et al.*, 1999; Ruiz *et al.*, 2000; Rosenzweig, 2001; Wonham *et al.*, 2001; Grosholz, 2002; Olden *et al.*, 2004). In regions where the uniqueness and diversity of native assemblages are of high conservation value there is the potential for NIS to have a significant impact by replacing native endemic species with cosmopolitan invaders. NIS and their associated impacts are being increasingly observed in marine environments throughout

the globe (Ruiz *et al.*, 1997; Cohen & Carlton, 1998; Ruiz *et al.*, 1999; Ruiz *et al.*, 2000; Hewitt, 2002, 2003; Hewitt *et al.*, 2004). Locations influenced by high levels of anthropogenic activity, such as ports and marinas, are generally the focus of surveys for introduced species (Hewitt & Martin, 2001; Hewitt, 2002), whereas locations of high conservation or World Heritage significance have rarely been examined from a biological invasions perspective (but see Lewis, 2001; Wasson *et al.*, 2001; Lewis *et al.*, 2003). The long history and continuing anthropogenic activity in shallow-water marine regions suggests that many areas identified and protected as marine reserves for natural values may in fact already be highly altered by exotic species (Carlton, 1989). Protection of

such areas should focus on preventing further invasion, since additional introductions are highly probable as long as the mechanisms and opportunities exist (Carlton, 1989, 2001).

Obligations under the World Heritage Convention (UNESCO, 1972) include the obligation to protect and conserve the World Heritage values of a property; to integrate the protection of the area into a comprehensive planning program and to take appropriate measures, including scientific, for the achievement of the foregoing objectives. Management of the property should allow for use that does not threaten World Heritage values and integrity. Given that few areas subject to anthropogenic activity remain free from the impacts of the three main threats to biodiversity (i.e. habitat degradation, over harvesting and NIS; Simberloff (2000)), conservation and active protection of the unique biota of World Heritage properties is likely to become increasingly important. This is especially so in the face of continued anthropogenic utilization, with case studies worldwide suggesting that the introduction and impacts of NIS increase with human use (Carlton, 1996b; Cohen & Carlton, 1998). Protection of values under the World Heritage Convention is dependent on managing anthropogenic activities in World Heritage properties to minimize introduction risk. This management is dependent on information regarding the mechanism, extent and likely impacts of realized and potential introductions.

In Western Australia, the need to identify patterns of anthropogenic activity in the Shark Bay World Heritage Property and the likely impacts, including those from NIS, on the ecology of the property and adjacent region, has been identified as a high funding and research priority (Simpson *et al.*, 2002). In this study, a preliminary investigation was conducted to provide information essential for managing marine introductions in the region.

Shark Bay: World Heritage and anthropogenic impact

Marine and terrestrial areas of the Shark Bay region were inscribed on the World Heritage List in 1991, one of the few inscribed for all four outstanding natural universal values (EA, 1999). As such it represents an outstanding example of the major stages in the earth's evolutionary history; an outstanding example of significant ongoing ecological and biological processes; an example of superlative natural phenomena; and it contains important and significant habitats for conservation of biological diversity (UNESCO, 1972).

The Bay itself is a 13,000 km² marine embayment located midway along the coast of Western Australia between the latitudes of 24°30' S and 24°45' S and the longitudes of 113° E and 114°20' E (Fig. 1). It is a generally shallow bay (average depth 9 m, maximum depth 29 m) protected by a line of islands and a long peninsula. The southern half is divided by the Peron Peninsula into eastern and western gulfs. The presence of three offshore islands limits exchange of water between the Bay and the shelf to three main channels (Burling *et al.*, 2003).

Limited exchange with the ocean, along with persistent winds and resulting high evaporation rates has led to elevated salinities and strong horizontal salinity gradients (Burling *et al.*, 1999; Burling *et al.*, 2003). The increase in salinity with distance from

the ocean is one of the key features of Shark Bay, and leads to its characterization as an inverse estuary (Wolanski, 1986; Largier *et al.*, 1997; Burling *et al.*, 1999).

A major feature of the Bay is the interplay between physical and biological processes in shaping the marine environment. Large seagrass beds and associated epiphytes are thought to have led to the formation of sills and banks, reducing exchange with the ocean and resulting in the Bay's hypersalinity and associated physical and biological phenomena (Logan *et al.*, 1970; Walker & Woelkerling, 1988; Walker, 1990). Many features of the marine environment have World Heritage value: three distinct biological zones caused by salinity gradients; restricted communities of marine organisms that have developed physiological adaptations to tolerate hypersaline conditions; great genetic variability in marine species; high species diversity and density of bivalves; and an abundance of marine fauna and seagrass-based ecosystems (EA, 1999).

The marine environment of Shark Bay is also of interest as it is a transition zone between major marine ecological provinces, including the northern limit of a transition between temperate and tropical marine fauna (Logan & Cebulski, 1970). The region is near the southern limit of the tropical Indo-West Pacific Biotic Province, but also has a mixture of temperate species and species endemic to Western Australia. As a consequence of the overlap resulting from the transition from tropical to temperate conditions, Shark Bay has high species diversity, with 323 fish species of predominantly tropical affinity (Hutchins, 1990), 218 bivalve species (74.8% tropical affinity, largely Indo-West Pacific) (Slack-Smith, 1990), 232 species of decapod crustacea (only 17 of temperate affinity, largely Indo-West Pacific) (Jones, 1990), 161 species of benthic macroalgae of largely tropical or cosmopolitan distribution (Kendrick *et al.*, 1990), and 80 coral species (Marsh, 1990).

The overlap of biotic provinces and mixture of temperate and tropical species in the Bay suggests that the potential exists for the establishment of a broad suite of NIS of both temperate and tropical origin. On the other hand, high species diversity resulting from the combination of temperate and tropical species may confer a resistance to invasion by NIS (Elton, 1958; Fox & Fox, 1986; Case, 1990; Vermeij, 1991; Stachowicz *et al.*, 1999; Lyons & Schwartz, 2001).

There is a long history of anthropogenic activity in Shark Bay prior to its recognition as an area of World Heritage importance. The Bay is the site of the first European landing in Western Australia, with the visit of Dirk Hartog in 1616, followed by William Dampier in 1699 (CALM, 2002). Anthropogenic activity has continued since these first landings within and adjacent to the World Heritage property. The Port of Carnarvon at the northern boundary of the property has been in operation for over 120 years and attracts significant commercial shipping to the Bay. Within the property itself, two exclusion zones exist where activities can be undertaken that would not necessarily be appropriate in the rest of the World Heritage area: a small township (Denham, population 950) and mining and ship loading of salt by the Shark Bay Salt Joint Venture (SBSJV) in Useless Loop and Useless Inlet. Both exclusion zones and the Port of Carnarvon are associated with vessel traffic within the Bay (Table 1). In addition, being the

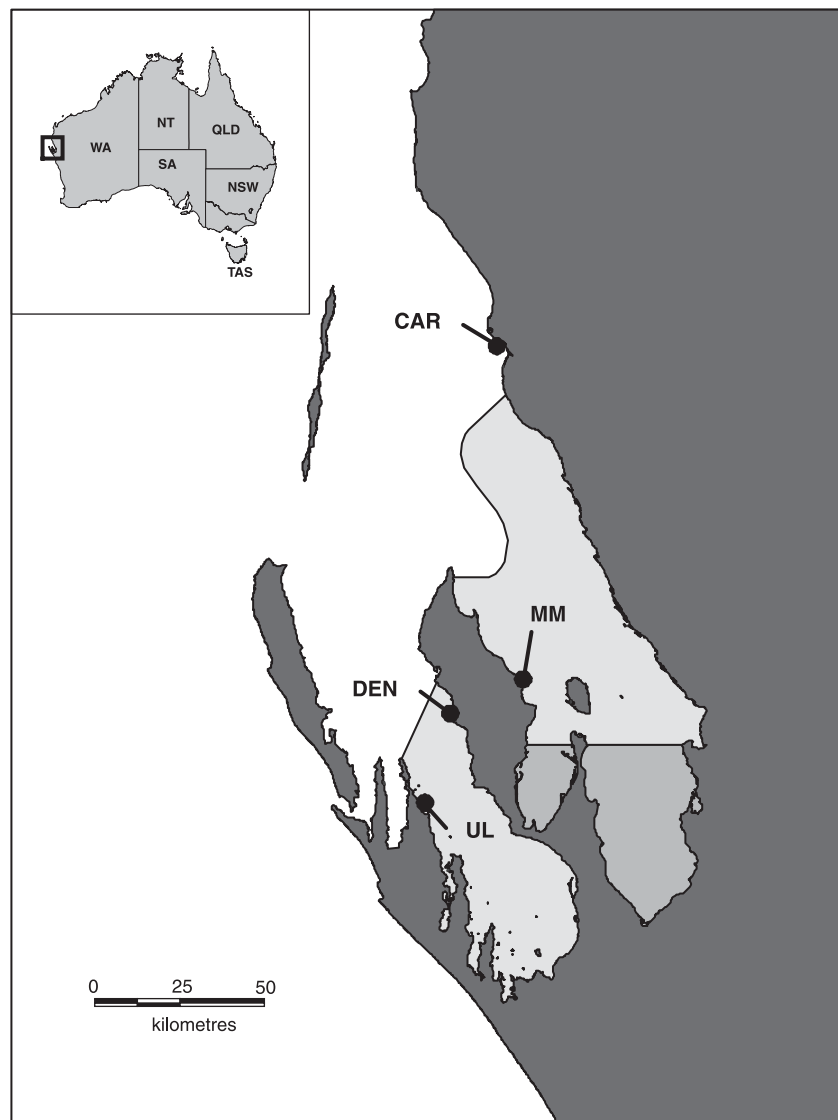


Figure 1 Shark Bay World Heritage Property, Western Australia detailing collection sites and approximate location of salinity zones identified by Logan & Cebulski (1970). Sites: Car — Carnarvon; MM — Monkey Mia; Den — Denham; UL — Useless Loop. Salinity Zones: white — Open Ocean (36–40 ppt); light grey — Metahaline (40–56 ppt); dark grey — Hypersaline (56–70 ppt).

only large marine embayment in the region, with Cockburn Sound over 800 km to the south and Exmouth Gulf 200 km to the north, the Bay receives visits by commercial and recreational vessels travelling up and down the coast, as well as from international vessels such as cruising yachts. Anthropogenic activity in the Bay also includes fishing and aquaculture. Leases and applications for expansions exist for pearl oyster cultivation, oyster spat collection and caged finfish culture (Fowler, 1996).

Despite the long history of anthropogenic use and potential impacts on unique native biota, there has been minimal investigation into the status of NIS in the Bay. In 2001, a survey was conducted in close proximity to the Useless Loop salt operations and in the shipping channel through which international vessels arrive to load salt, and where they discharge ballast. The survey did not reveal any marine pests listed by the Australian Ballast Water Management Advisory Council, but did discover a cosmopolitan introduced barnacle (*Megabalanus tintinnabulum*) (SKM, 2001).

In this study, we focused on sites primarily associated with commercial and recreational vessels as these were identified as

the most significant introduction vectors. Encrusting communities were chosen as the focus of the survey for a number of reasons: (1) multiple vectors act in Shark Bay (hull fouling, ballast water, aquaculture), all of which transport encrusting species; (2) encrusting NIS have the potential to significantly impact some of the region's World Heritage values (e.g. seagrass communities); and (3) fouling communities are tractable systems, easy to manipulate and rapid in growth. Given the short time scale of this study, fouling communities represented the best option to quickly and easily assess the presence of NIS in Shark Bay's marine environment.

METHODS

Survey design

The presence and identity of NIS amongst Shark Bay's encrusting communities and the potential influence of anthropogenic activity and native species diversity on their distribution within the Bay were investigated by a focused fouling plate survey. Sites were

Table 1 Details of 4 study sites, including the number of fouling plates deployed, the environment in terms of salinity zone identified by Logan & Cebulski (1970) (and measured between April and August 2002*), and details of vessel traffic in terms of numbers of vessels visiting/operating at the site

Site (no. of Plates Recovered/ no. of Plate Deployed)	Environment (salinity*)	No. of Vessels	Type of Traffic/Comments	References
Useless Loop (4/20)	Metahaline (40)	48–80 per annum	Ballasted salt ships arrive in Shark Bay full of ballast water to load salt. SBSJV requires that all ships have re-ballasted in open ocean before entering Australian waters. Shipmasters are required to maintain logs of such re-ballasting including latitudes and longitudes at which they occur. SBSJV records these details. Nothing but open ocean ballast water may be discharged while ships arrive, depart or load salt at Useless Loop.	(SKM, 2002) (SKM, 2001) (EPA, 1998)
Carnarvon (20/20)	Oceanic (38–40)	65 + operating vessels	Vessels operate in Shark Bay Managed Snapper, Scallop and Prawn Fisheries and berth in Carnarvon. In addition Western Rock Lobster (WRL) fishing craft from Geraldton operate in Shark Bay. Tug boats associated with Cape Cuvier salt moor at the Carnarvon site. These vessels are likely to interact with international vessels arriving to load salt.	(Shaw, 2000) (Anecdotal)
Denham (20/20)	Metahaline (40–42)	Uncertain	Some small commercial fishing vessels and Geraldton registered WRL fishery craft. Recreational traffic very difficult to quantify.	(Anecdotal)
Monkey Mia (20/20)	Metahaline (42)	Uncertain	Recreational traffic very difficult to quantify. Some tourism-based vessels (two main craft) operate throughout the Bay from Monkey Mia.	(Anecdotal)

selected on the basis of association with vessel traffic (following Hewitt & Martin, 2001) and available substratum for deployment of materials.

Sites were selected that varied in the type and amount of anthropogenic influence experienced (Table 1), ranging from international/commercial traffic at the Useless Loop Salt Works (Slope Island Shipping Berth), shipping channels leading into the Bay (South Passage, Blind Strait and Denham Channel), and Carnarvon Boat Harbour to predominately domestic/recreational traffic at Denham and Monkey Mia (Fig. 1). Sites also varied in physical environment. Salinity varies greatly in the Bay, with distinct salinity zones having previously been identified from oceanic (36–40 ppt), to metahaline (40–56 ppt) and hypersaline (56–70 ppt) (Logan & Cebulski, 1970). An attempt was made to control for the possible influence of salinity variation on fouling communities by deploying plates at sites in each of the zones identified by Logan & Cebulski (1970), excluding the hypersaline zone where there is little anthropogenic influence and biological activity is likely to be limited.

Fouling plate deployment and retrieval

A total of 82 fouling plates (210.25 cm²: 145 × 145 × 3 mm squares of PVC, sand blasted on one side) were deployed during April 2002 (Table 1). Plates were attached to a brick and suspended by rope from available structures (jetties) such that they hung approximately 0.5 m below Mean Low Water with the sand-blasted side facing down in full shade. Plates were retrieved in late June 2002 (after 67 days at Denham, Useless Loop and Carnarvon; after 65 days at Monkey Mia) and photographed *in situ* with a Nikonos V fitted with a close-up lens where possible

(Monkey Mia and Carnarvon). Twenty plates each were retrieved from Monkey Mia, Denham and Carnarvon and four plates from Useless Loop. All plates in the more exposed shipping channels (South Passage, Blind Strait and Denham Channel) could not be relocated and were presumably lost in strong storms that occurred prior to collection. Collection was achieved by placing plates in snap-lock plastic bags while underwater to prevent damage to encrusting species.

Immediately after collection, whole plates and water from collection bags were transferred to a nylon stocking and relaxed in 6% MgCl₂ for approximately 30 min. Plates were then transferred to 10% formalin (buffered with seawater) prior to transport to Perth. Within 2 weeks after collection, all plates were transferred to 70% ethanol.

Plates were examined under a dissecting microscope and species cover was estimated by grid point analysis. A 20-point fixed (non-random) grid was placed over the centre of the plate and the morphotype (solitary or colonial; sheet, runner, erect) of each recognizable species attached to the plate was recorded. Species occupying secondary space below the grid point were also recorded to morphotype. Voucher specimens of every observed morphotype on the plate were taken and placed in vials containing unique ID codes with 70% ethanol. A sample of every morphotype was placed in a reference collection, which included samples of the same morphotype observed on other plates. This collection, along with samples from each plate, is maintained at the Western Australian Museum (WAM).

Species not recorded in the point count frequency analysis but detected in the whole plate evaluation were assigned an arbitrarily low cover value of 0.5% (species occupying less than 5% cover would not be expected to be sampled by grid points at the density

used here). Percent cover of each morphotype captured by grid analysis was subsequently calculated using the following equation:

$$\text{species cover} = \left(\frac{\text{No. of counts}}{20} \right) \times (100 - (0.5 \times \text{No. of species not captured}))$$

All voucher material was examined by a number of experts (molluscs — Shirley Slack-Smith and Di Jones, WAM; hydroids — Jan Watson, Hydrozoan Research Laboratory; ascidians — Francois Monniot, Biologie des Invertebres Marins; bryozoans — CLH). Specimens were identified where possible to species, and otherwise to the lowest taxonomic unit (LTU). In many cases it was not possible to identify specimens to species or even genus due to taxonomic difficulties associated with identifying young or juvenile specimens.

Following the identification process, all species were scored as to whether they were native, introduced or cryptogenic (*sensu* Carlton, 1996a). Determination of species status was based on published lists of species that are introductions to Australia (Pollard & Hutchings, 1990; Furlani, 1996; Hewitt, 2002; Hewitt *et al.*, 2004) and on expert opinion (CLH).

Data analysis

Statistically significant differences between survey sites were examined by one-way analysis of variance (ANOVA). Significant results are quoted in terms of F- and P-values. Species-area curves and species richness estimators were calculated for each site based on 1000 permutations in EstimateS (Colwell & Coddington, 1994; Colwell, 1997). The two most appropriate species richness estimators for this particular data set were MM Mean (based on the Michaelis-Menton equation) and Chao 2 (Chao, 1987). These species richness estimators were compared to the final point attained in the species accumulation curves to determine the percentage of species sampled relative to the total number estimated to be present for successively more sites and plates within each site (Table 2). The derivative of the logarithmic equation representing each species-area curve was used to determine the number of plates that would be required at each site such that an additional plate would only add 0.1 of a species.

Community diversity for each plate was estimated using the Shannon-Weaver information index (H' ; Shannon & Weaver, 1949). This index calculates species contribution to live cover (the total space occupied by living organisms):

$$H' = -\sum p_i \ln(p_i)$$

where p_i is the proportion of all occupied space occupied by the i -th species (% cover of the i -th species / total cover on each fouling plate).

RESULTS

Vectors

Vessel traffic varied in intensity for each sample location (Table 1). Vessel activity ranged from moderate numbers of large commercial

Table 2 Measured species richness (Total) and species richness estimates (MM = Michaelis-Menton mean and Chao2) for the entire community, the native (*including cryptogenic species) and introduced components. Species richness estimates include a presentation of the percentage of the estimate measured (Total/species richness estimator)

	Total	MM	Chao2
Carnarvon			
ALL	31	30.89 (100.3)	31.43 (98.6)
Native*	24	23.55 (101.9)	24.50 (97.9)
Introduced	7	7.5 (93.3)	7.00 (100.0)
Monkey Mia			
ALL	50	49.21 (101.6)	50.86 (98.3)
Native*	46	45.55 (100.1)	46.72 (98.5)
Introduced	4	4.05 (98.8)	3.89 (102.8)
Denham			
ALL	40	39.37 (101.6)	41.01 (97.5)
Native*	38	37.33 (101.8)	39.07 (97.3)
Introduced	2	2.18 (91.7)	2.00 (100.0)
Useless Loop			
ALL	23	24.56 (93.6)	25.05 (91.8)
Native*	21	17.81 (117.9)	20.97 (100.2)
Introduced	2	—	—

vessels of international origin at Useless Loop, to very limited numbers of recreational vessels at Monkey Mia. While discharge of ballast water is a potential vector associated with large commercial vessels visiting Useless Loop and Carnarvon, hull fouling is the most likely means for recreational craft to translocate species (since vessels are smaller, do not carry much cargo and hence lack ballast water). The actual movement of recreational vessels into and within the Bay is not currently possible to determine, consequently a full analysis of the hull-fouling vector must be deferred.

Non-indigenous species

Of the 112 encrusting taxa collected, a total of 10 (11.2%) were classified as introduced and 10 others as cryptogenic. Eight introduced bryozoans: *Aetea anguina* (Linnaeus, 1758), *Bugula neritina* (Linnaeus, 1758), *Bugula stolonifera* Ryland, 1960, *Conopeum seurati* (Canu, 1928), *Savignyella lafontii* (Audouin, 1826), *Schizoporella errata* (Waters, 1878), *Watersipora subtorquata* (d'Orbigny, 1842) and *Zoobotryon verticellatum* della Chiaje, 1828; one tunicate, *Styela plicata* Lesueur, 1823; and an introduced hydroid, *Obelia dichotoma* (Linnaeus, 1758) were frequent, and in some cases dominant, components of encrusting communities at each site (Tables 3 and 4). Of the 20 most frequently occurring species detected in the Bay, four were introduced. In particular, two individual NIS were remarkably common; the two bryozoans *Schizoporella errata* and *Watersipora subtorquata*, occurred on 75% and 58% of fouling plates, respectively. Four of the NIS had multisite distributions with one species (*Schizoporella errata*) detected at all sites. Conversely, a number of species were unique to single sites, including *Zoobotryon verticellatum* at Denham and *Aetea anguina* at Monkey Mia.

Table 3 Introduced species showing percentage of plates and the sites from which they were sampled in Shark Bay, as well as their likely origin/range, temperate/tropical affinity (+ = prevalent, + = present, - = absent, ? = unknown) (after Hewitt (2002))

Species	Frequency (%)	Sites	Origin/Range	Tropical	Temperate
Introduced					
<i>Schizoporella errata</i>	75	All	Cosmopolitan; NW Atlantic	+	++
<i>Watersipora subtorquata</i>	58	All (excluding Useless Loop)	W Pacific	+	++
<i>Styela plicata</i>	31	Carnarvon	W Pacific	-	+
<i>Conopeum seurati</i>	30	Carnarvon, Monkey Mia	Cosmopolitan; NE Pacific	+	++
<i>Bugula stolonifera</i>	25	Carnarvon	Cosmopolitan	+	++
<i>Aetea anguina</i>	23	Monkey Mia	—	+	++
<i>Savignyella lafontii</i>	22	Carnarvon	Cosmopolitan	++	+
<i>Bugula neritina</i>	8	Carnarvon	Cosmopolitan; NE Atlantic	++	++
<i>Obelia dichotoma</i> (= <i>australis</i>)	6	Useless Loop	Cosmopolitan; NE Atlantic	-	+
<i>Zoobotryon verticellatum</i>	2	Denham	Cosmopolitan	+	++
Cryptogenic					
<i>Diplosoma</i> sp.	47	Carnarvon, Denham	—	?	?
Folliculinid	28	Useless Loop, Denham	—	?	?
<i>Corophium</i> sp.	14	Carnarvon	—	-	+
<i>Bowerbankia</i> sp.	13	Denham	Cosmopolitan	?	?
<i>Leucartia</i> ?	9	Denham	—	?	?
<i>Polysiphonia</i> sp.	6	Denham Monkey Mia	—	?	?
<i>Sarsia eximia</i>	3	Useless Loop	Cosmopolitan	-	+
<i>Botrylloides leachi</i>	2	Denham	NE Atlantic	+	-
<i>Clytia hemisphaerica</i>	1	Useless Loop	Cosmopolitan	+	-
<i>Bougainvillia</i> sp.	1	Useless Loop	Cosmopolitan	+	-

Table 4 Average percent cover per plate (\pm standard error) of the 10 most abundant species at each site, showing morphotype or species identification where possible and native (N), introduced (I) or cryptogenic (C) status

Carnarvon		Useless Loop		Denham		Monkey Mia	
Ascidian 7	N 7.92 \pm 3.8	<i>Obelia dicotoma</i>	I 2.02 \pm 8.2	Spiroid 1	N 1.56 \pm 1.3	Serpulid 3	N 1.23 \pm 0.94
<i>Styela plicata</i>	I 7.82 \pm 3.5	Folliculinid	C 0.608 \pm 5.5	<i>Didemnum</i> sp.	N 0.617 \pm 0.66	<i>Schizoporella errata</i>	I 0.876 \pm 0.95
<i>Balanus amphitrite</i>	N 2.55 \pm 2.1	<i>Schizoporella errata</i>	I 0.157 \pm 1.3	<i>Diplosoma listerianum</i>	C 0.425 \pm 0.66	Hydroid X	N 0.527 \pm 1.1
<i>Diplosoma listerianum</i>	C 2.40 \pm 1.2	Bivalve 1	N 0.0313 \pm 0	<i>Obelia dicotoma</i>	N 0.384 \pm 0.54	Sabellid 2	N 0.459 \pm 0.55
<i>Schizoporella errata</i>	I 1.81 \pm 1.2	<i>Didemnum</i> sp.	N 0.0234 \pm 0.13	Serpulid 3	N 0.280 \pm 0.29	<i>Aetea anguina</i>	I 0.449 \pm 0.54
Serpulid 1	N 0.908 \pm 1.7	? <i>Diphasia</i>	N 0.0234 \pm 0.13	Folliculinid	C 0.259 \pm 0.46	Loxosomatid	N 0.431 \pm 1.4
Ascidian 8	N 0.481 \pm 0.43	Foram 1	N 0.0234 \pm 0.123	Ascidian 15	N 0.230 \pm 0.39	Tunicate 6	N 0.146 \pm 0.47
<i>Kirchenpaueria irregularis</i>	N 0.416 \pm 0.40	<i>Hippothoa</i> sp.	N 0.0156 \pm 0.14	Ascidian 7	N 0.219 \pm 0.70	Spiroid 1	N 0.141 \pm 0.034
<i>Conopeum seurati</i>	I 0.397 \pm 0.40	Sponge 1	N 0.0156 \pm 0.14	<i>Schizoporella errata</i>	I 0.136 \pm 0.23	Foram 1	N 0.133 \pm 0.041
Spiroid 1	N 0.350 \pm 0.36	<i>Sarsia eximia</i>	C 0.0156 \pm 0.14	<i>Bowerbankia</i> sp.	C 0.130 \pm 0.24	<i>Polysiphonia</i> sp.	N 0.133 \pm 0.041

The encrusting communities varied between sites. Significant differences in terms of total richness ($F_{[3,60]} = 22.21$; $P < 0.0001$), total primary biogenic cover ($F_{[3,60]} = 140.7$; $P < 0.0001$) and diversity (H') ($F_{[3,60]} = 5.966$; $P < 0.01$) were detected, presumably in response to conditions of temperature and salinity, which varied by as much as 2.5 °C and 5.0 ppt. Pairwise tests revealed that significant differences in total richness and total primary biogenic cover existed between all sites with three exceptions: total richness between Useless Loop and Monkey Mia ($F_{[1,22]} = 0.2917$;

$P > 0.05$), Useless Loop and Denham ($F_{[1,22]} = 1.493$; $P > 0.05$) and total primary biogenic cover between Monkey Mia and Denham ($F_{[1,38]} = 0.3278$; $P > 0.05$). Significant differences in diversity occurred between Useless Loop and all other sites (Carnarvon: $F_{[1,22]} = 12.82$; $P < 0.01$; Denham: $F_{[1,22]} = 12.86$; $P < 0.01$; Monkey Mia: $F_{[1,22]} = 11.89$; $P < 0.01$).

NIS were detected at every site, however, the richness and identity of NIS varied between sites: Carnarvon had seven introduced species (32% of total richness), Monkey Mia had four

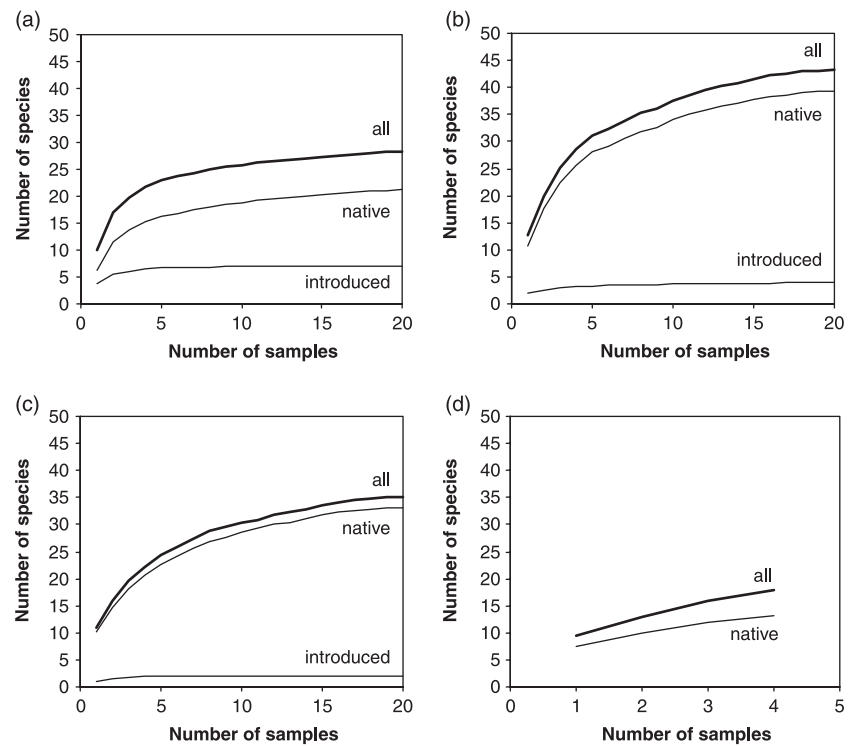


Figure 2 Species accumulation curves based on 1000 permutations for the entire community (all), and the native (including cryptogenic species) and introduced components. (a) Carnarvon (20 plates); (b) Monkey Mia (20 plates); (c) Denham (20 plates); and (d) Useless Loop (4 plates).

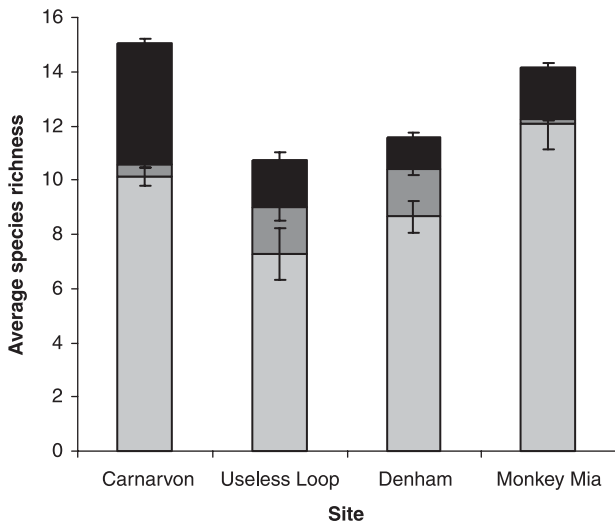


Figure 3 Average species richness per plate (\pm se) at each site for native (light grey), cryptogenic (dark grey), and introduced (black) species.

(9%), Denham two (5%) and Useless Loop two (9%) (Fig. 3; Table 2). However, note that the two NIS at Useless Loop were detected from four plates, compared to 20 plates used at each of the other sites.

The species richness estimators (MM and Chao2) suggest that the true numbers of species in the entire community and native component were well described (Table 2), however, inspection of the species-area curves demonstrated that the number of plates sampled at each site was insufficient to fully elucidate the entire encrusting community or the native component (including cryptogenic species) (Fig. 2). Using the logarithmic equation, the calculated

number of plates necessary to sample the entire community was: 56 plates at Carnarvon, 104 at Monkey Mia, 85 at Denham and 61 at Useless Loop; and the native component: 46 plates at Carnarvon, 97 at Monkey Mia, 82 at Denham and 44 at Useless Loop.

The introduced species components of the communities appear to have been well sampled at Carnarvon, Monkey Mia and Denham (Fig. 2; Table 2). The data was insufficient at Useless Loop to evaluate the efficacy of sampling. The calculated number of plates necessary to sample the introduced component of the community was: nine plates at Carnarvon, seven at Monkey Mia and four at Denham.

Introduced species were significant space occupiers (Table 4). Six of the 20 species with highest average bay-wide percent cover per plate were identified to be NIS. *Styela plicata* averaged $7.82\% \pm 1.8$ of plate cover, *Schizoporella errata* $2.98\% \pm 0.54$, *Obelia dichotoma* $2.02\% \pm 1.0$, *Aetea anguina* $0.459\% \pm 0.19$, *Watersipora subtorquata* $0.422\% \pm 0.10$, and *Conopeum seurati* $0.413\% \pm 0.14$. At the level of site, very high space occupation by NIS occurred at Useless Loop ($71.6\% \pm 7.4$ of live cover) and Carnarvon ($39.3\% \pm 3.7$) (Fig. 4). Space occupation by an individual NIS was as high as 62.4% of plate area, achieved by the tunicate *Styela plicata* on a plate at Carnarvon (where average plate live cover was significantly higher than elsewhere). At the same site the bryozoan *Schizoporella errata* achieved as much as 18.5% cover and together the two invaders averaged 36.5% of live cover per plate. With an average of 85% plate live cover, Carnarvon was the only site for which secondary cover was observed — 38.5% of overgrowing species were introduced and 8% cryptogenic.

Despite the significantly different native communities, a significant influence of native diversity on the diversity of NIS was not observed in this study. While native richness and diversity

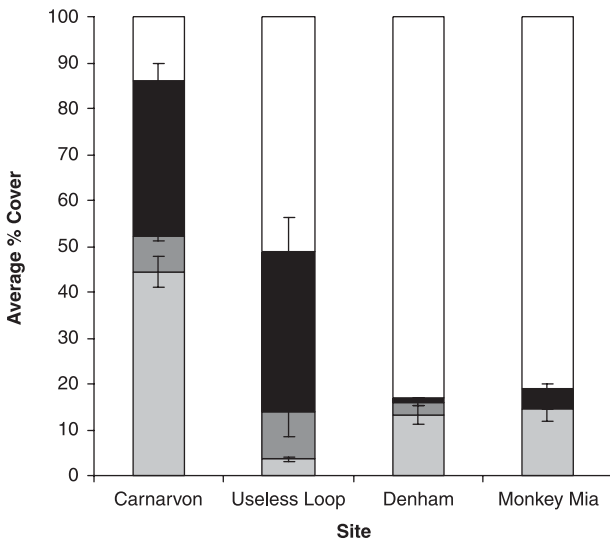


Figure 4 Average percentage primary cover per plate (\pm se) of native (light grey), cryptogenic (dark grey), and introduced (black) species and bare space (empty).

(H') was significantly different between sites ($F_{[3,60]} = 22.21$; $P < 0.001$ and $F_{[3,60]} = 5.966$; $P < 0.01$, respectively), no relationship between native richness with introduced species richness was observed ($r^2 = 0.0395$; $F_{[1,62]} = 2.552$; $P = 0.1153$).

While the vector for introduction of each NIS detected cannot be determined, life history traits (e.g. sessile benthic adult, short or no larval duration) suggest that, apart from the cryptogenic *Corophium* species, hull fouling is a more likely vector than ballast water for every introduced and cryptogenic species detected (Table 3). Also all species introduced to Denham and Monkey Mia have most likely been introduced by hull fouling of recreational craft, with limited commercial traffic to these sites.

Of the NIS in Shark Bay most are present in the Ports of Bunbury and Fremantle to the South of the Bay (75%), while few are established to the north in Port Hedland and Darwin (33%) (Table 5). Using this as a proxy for temperate (present in southern ports) and tropical (present in northern ports) affinity, it would appear that a disproportionate amount of NIS detected in the Bay are of temperate affinity, in contrast to much of the native biota which has tropical affinity (74.8% of bivalves and 92.7% of decapod crustacea; Jones, 1990; Slack-Smith, 1990).

Taxonomic experts could not identify a substantial component of the material collected during the survey to species or even genus level (65.7%). Although many of the unidentified taxa are likely to be native to Australia, they have not been rigorously evaluated to determine their native or introduced status and therefore should be considered cryptogenic (native origin unknown, see Carlton (1996a)). For the purpose of conservative analyses however, unidentified species were considered to be native in this study.

DISCUSSION

This study presents a preliminary assessment of marine introductions in the Shark Bay World Heritage Property. It

Table 5 Distribution of Shark Bay’s introduced species in major Australian ports likely to be linked to Shark Bay by domestic vectors (+ = present, – = absent) based on data from P. Arnold, unpublished report (Darwin); Hewitt *et al.* 1999a (Port Hedland); Hewitt *et al.* 2000 (Fremantle); & Hewitt *et al.* 1997 (Bunbury)

Species	Port			
	Darwin	Hedland	Fremantle	Bunbury
Introduced				
<i>Schizoporella errata</i>	–	–	+	+
<i>Watersipora subtorquata</i>	+	–	+	+
<i>Styela plicata</i>	–	–	+	–
<i>Conopeum seurati</i>	–	–	–	+
<i>Bugula stolonifera</i>	–	+	+	+
<i>Aetea anguina</i>	–	–	–	–
<i>Savignyella lafontii</i>	+	–	–	–
<i>Bugula neritina</i>	+	+	+	+
<i>Obelia dichotoma</i> (= <i>australis</i>)	–	–	+	+
<i>Zoobotryon verticellatum</i>	+	–	+	–
Cryptogenic				
<i>Diplosoma</i> sp.	–	–	–	–
<i>Folliculinid</i>	–	–	–	–
<i>Corophium</i> sp.	–	–	–	+
<i>Bowerbankia</i> sp.	–	–	+	–
<i>Leucartia?</i>	–	–	–	–
<i>Polysiphonia</i> sp.	–	–	–	–
<i>Sarsia eximia</i>	–	–	+	–
<i>Botrylloides leachi</i>	–	–	+	+
<i>Clytia hemisphaerica</i>	–	–	+	–
<i>Bougainvillia</i> sp.	–	–	+	–

demonstrates that NIS are present within the World Heritage Property and are significant components of encrusting communities associated with artificial habitats.

The study also highlights the potential for hull fouling and recreational craft to be a significant vector in the translocation of marine species. The apparent influence of hull fouling and recreational craft on introductions is not unique to this study. In regions influenced by vessels that do not utilize ballast water, hull fouling may be the most important vector, particularly in situations where vessels remain in ports for extended periods (Floerl, 2001; Hewitt & Martin, 2001; Paulay *et al.*, 2002). The threat due to hull fouling has been strongly confirmed by the Black-striped mussel (*Mytilopsis sallei*) incursion in Darwin, with heavy mussel infestations found on the hulls of recreational yachts and suggested as the mechanism for the mussel’s spread between marinas (Thresher, 1999; Campbell & Hewitt, *submitted*). Sixty per cent of introductions to Port Philip Bay are associated with hull fouling (Hewitt *et al.*, 1999b; Hewitt *et al.*, 2004), while in tropical Australia 84.7% are associated with hull fouling (Hewitt, 2002).

In Shark Bay, the presence of NIS unique to Denham (*Zoobotryon verticellatum*) and Monkey Mia (*Aetea anguina*) suggests that hull fouling of recreational craft may be a more significant vector in the World Heritage Property than previously considered. While the stepping-stone nature of many introductions suggests

the capacity for species to be introduced by commercial shipping vectors at Useless Loop and Carnarvon and thereby spread to Denham and Monkey Mia, intrabay dispersal of species by natural means is likely to be limited by strong tidal density fronts (Apte *et al.*, 2000; Nahas *et al.*, 2003). Anthropogenic movement between sites within the Bay is unlikely, particularly from Useless Loop where there is little to no visitation other than by salt-carrying vessels. This study suggests that hull fouling of recreational vessels is resulting in introductions to the World Heritage Property.

International shipping and ballast water discharge is generally considered to be the principal vector in marine introductions and, while this study suggests that hull fouling of recreational craft is a significant vector, the influence of international shipping is harder to discern. The long history of commercial shipping at Carnarvon is one explanation for higher introduced richness at this site. At Useless Loop, the small number of fouling plates recovered and the focus on encrusting taxa makes the influence of salt-carrying ships, and in particular their ballast discharge, hard to gauge. Many more plates would be required to fully sample the community and determine the full extent of invasions at that site.

Comparison of NIS amongst encrusting and pelagic communities is one way to further elucidate the roles that hull fouling and ballast water play in species introductions in the Bay. In Guam, a preponderance of sessile species in the non-indigenous fauna has been used to support the importance of hull fouling, compared with ballast transport, as the main source of introduced species (Paulay *et al.*, 2002). In Shark Bay, more widespread surveying is required to determine the influence of the two vessel-related vectors. In particular, direct sampling of ballast water being discharged into the Bay has not yet been undertaken.

The distribution of NIS away from potentially impacted sites into natural habitats in the Bay has not been determined. The difference in encrusting communities on natural and artificial substrata has been clearly demonstrated (Glasby, 1999) and it may be that NIS, particularly those introduced via hull fouling, may have a preference for artificial habitats (Glasby *et al.*, unpublished data; Paulay *et al.*, 2002). It may be that undisturbed native communities in Shark Bay have greater resistance to invasion than communities in the disturbed habitats studied (Ruiz *et al.*, 1997; Simberloff & Von Holle, 1999; Ruiz *et al.*, 2000; Sousa, 2001). However there is debate regarding the relationship between disturbance and invasion (see Cohen & Carlton, 1998). In the current study, biotic resistance to invasion was not evident and in an unpublished study the impact of disturbance on invasion of Shark Bay's encrusting communities was not convincingly demonstrated (Wyatt, 2002). The ability of the NIS detected in this study to spread to natural habitats should be a priority for further research.

No attempt was made to quantify impact of NIS in this study, however, observations of NIS worldwide suggest that, should significant establishment of NIS occur in natural habitats, there is a great potential for these species to impact on the native biota of Shark Bay. Examples of potential impacts include the introduced hydroid *Obelia dichotoma*, which dominated cover in encrusting communities at Useless Loop. This species has the potential to

negatively influence recruitment of native species. The hydroid inhibits settlement of other invertebrates, partly by eating the larvae (see Gili *et al.* (1996) and references therein). The ability of *O. dichotoma* to impair native settlement is likely to be enhanced by its high cover at Useless Loop. Similarly, high cover of the bryozoan *Zoobotryon verticellatum* is likely to enhance the species influence on native organisms. *Z. verticellatum* was not observed in either April or June at Denham, but in August formed a conspicuous thick covering over jetty pylons, growing outwards up to c. 30 cm (A.S.J.W., pers.obs.).

At Carnarvon, the dominance and potential impacts of another two introduced species were of particular interest due to their abundance: the tunicate *Styela plicata*, and the bryozoan *Schizoporella errata* together accounted for an average of 36.5% of live cover per plate. In other studies, these two species have been shown to develop dense monocultures which resist the settlement of other species and thus have the propensity to hold space and persist for long periods of time (Sutherland, 1978). The adults of both species are good competitors, able to gain and hold space and hence may have the potential to exclude native encrusters in the Bay (Sutherland, 1978).

A number of NIS in this study have the capacity to establish in natural habitats of the Bay. Observations of *S. errata* in northern Florida suggest that the species is able to become established in soft sediment environments by forming colonies around small shell fragments, seagrass blades and worm tubes (Connell & Keough, 1985). In North America, *Bugula neritina* is known to establish on seagrass leaves (Hewitt *et al.*, 2002). The role and impacts of NIS as seagrass epiphytes in Shark Bay requires further examination.

Even in the absence of observation of direct impacts from the NIS detected in the Bay, the species should be viewed as a threat to World Heritage Values. Firstly, the addition of cosmopolitan human-commensal species (those with world-wide distributions as a result of association with human activities such as shipping) to Shark Bay reduces the uniqueness and conservation value of the region through making the biota more similar to other marine regions and furthering worldwide biotic homogenization (McKinney, 1998; Rosenzweig, 2001). Secondly, even apparently innocuous NIS with no obvious impacts, perhaps restricted to artificial habitats, may ultimately have significant impacts on natural communities (Simberloff, 2000). Many NIS remain in low densities for some time after introduction before becoming invasive and having significant impacts (Crooks & Soulé, 1999). Given the stepping stone nature of many marine invasions (Carlton, 1996b; Apte *et al.*, 2000), and the potential for intra-regional spread of NIS (Lavoie *et al.*, 1999; Wasson *et al.*, 2001) no invasion, even if on a small scale and localized, should be viewed as trivial.

Even if the NIS detected in artificial habitats in this study remain localized to these habitats, they have the potential to impact native biota. It is recognized that NIS may facilitate additional invasions (Simberloff & Von Holle, 1999). The facilitative ability of a number of introduced species detected in this survey has been documented. Colonies of *S. errata* are often colonized by a variety of other native and non-native species (Connell &

Keough, 1985). Establishment of *S. errata* in natural habitats of the Bay, such as seagrass meadows or soft sediment environments (Connell & Keough, 1985), may facilitate the development of encrusting communities (of natives or NIS) where they were previously absent. Species of *Watersipora* are also thought to provide a surface for other fouling organisms to settle on, which otherwise would not be able to become established (Hewitt *et al.*, 2002). *Bugula neritina* is known to settle and grow on another introduced species, the tunicate *Styela plicata* (Hewitt *et al.*, 2002).

The distribution of the Shark Bay NIS within other Australian ports suggest that southern temperate ports are more likely to be NIS donor regions than are northern tropical ports. Whether this is related to relative vector strength or to a greater opportunity for establishment of temperate species is difficult to determine, especially given the complete lack of information regarding the movement of recreational craft around Australia (Floerl, 2001). While *diversity-enhanced* resistance to invasion has not been demonstrated in this study, the high diversity of tropical systems has previously been suggested as a possible reason for fewer detected tropical marine introductions (Hewitt, 2002). One hypothesis that requires testing is that the higher diversity of tropical species in Shark Bay, may limit invasion by tropical NIS, while lower temperate diversity (Hutchins, 1990; Jones, 1990; Kendrick *et al.*, 1990; Slack-Smith, 1990) may make the region more susceptible to invasion by temperate species such as those established in southern Australian ports.

While a list of risk species is impossible to compile due to the almost limitless suite of potential invaders (Carlton, 1996b; but see Hayes & Sliwa, 2003), using information from species' environmental tolerances and their presence in other Australian ports (Hewitt *et al.*, 2002) suggests that a number of high impact pests species pose a significant threat to Shark Bay. For instance, in common with the species detected in this study, a number of recognized high-impact pest species that are established in Fremantle (*Sabella spallanzanii*, *Carcinus maenas* and *Crassostrea gigas*) and Bunbury (*Sabella spallanzanii*) have the ability to survive and reproduce in Shark Bay.

Conclusions

Ultimately no area subject to human utilization can remain free from marine introductions. Preservation of a region such as Shark Bay, conserved for its unique marine biota under the World Heritage Convention, requires management action to minimize the introduction, spread and ultimately, impacts, of non-indigenous species. This study has revealed that NIS are a frequent and abundant component of encrusting communities in Shark Bay and that these species may have the ability to negatively impact native biota. The importance of hull fouling of recreational craft has been reinforced by the presence of NIS that are unique to sites apparently uninfluenced by commercial traffic and ballast water discharge. Whether due to vectors, environmental conditions or biotic resistance, temperate invaders have tentatively been implicated as a greater risk to the region and, by association, the movement of vessels from Australian ports south

of Shark Bay should be treated as an increased risk. The extent to which ballast water creates a significant threat to Shark Bay, relative to hull fouling associated with recreational traffic, remains to be determined. Similarly, the capacity for NIS to establish within natural habitats of the Bay, where their impacts on native biota and World Heritage values may be significant, remains unknown.

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REFERENCES

- Apte, S., Holland, B.S., Goodwin, S. & Gardner, J.P.A. (2000) Jumping ship: a stepping stone event mediating the transfer of a non-indigenous species via a potentially unsuitable environment. *Biological Invasions*, **2**, 75–79.
- Burling, M.C., Ivey, G.N. & Pattiaratchi, C.B. (1999) Convectively-driven exchange in a shallow coastal embayment. *Continental Shelf Research*, **19**, 1599–1616.
- Burling, M.C., Pattiaratchi, C.B. & Ivey, G.N. (2003) The tidal regime of Shark Bay, Western Australia. *Estuarine, Coastal and Shelf Science*, **57**, 1–11.
- CALM (2002) *Cultural Heritage*. CALM. (http://www.sharkbay.org/world_heritage/page_07.htm — Accessed: 27/10/2002).
- Campbell, M.L. & Hewitt, C.L. (submitted) Lessons from a marine incursion response: eradication of *Mytilopsis sallei* in Darwin, Australia. *Ecological Applications*.
- Carlton, J.T. (1989) Man's role in changing the face of the ocean: biological invasions and implications for conservation of near-shore environments. *Conservation Biology*, **3**, 265–273.
- Carlton, J.T. (1996a) Biological invasions and cryptogenic species. *Ecology*, **77**, 1653–1655.
- Carlton, J.T. (1996b) Pattern, process, and prediction in marine invasion ecology. *Biological Conservation*, **78**, 97–106.
- Carlton, J.T. (2001) *Introduced species in US coastal waters: environmental impacts and management priorities*. Pew Oceans Commission, Arlington, Virginia.
- Case, T.J. (1990) Invasion resistance arises in strongly interacting species-rich model competition communities. *Proceedings of the National Academy of Sciences of the United States of America*, **87**, 9610–9614.
- Chao, A. (1987) Estimating the population size for capture-recapture data with unequal catchability. *Biometrics*, **43**, 783–791.
- Cohen, A.N. & Carlton, J.T. (1998) Accelerating invasion rate in a highly invaded estuary. *Science*, **279**, 555–558.
- Colwell, R.K. (1997) *Estimates: Statistical estimation of species richness and shared species from sample*. Version 6. University of

- Connecticut. (<http://viceroy.eeb.uconn.edu/EstimateS> — Accessed: 22/04/2004).
- Colwell, R.K. & Coddington, J.A. (1994) Estimating terrestrial biodiversity through extrapolation. *Philosophical Transactions of the Royal Society (Series B)*, **345**, 101–118.
- Connell, J.H. & Keough, M.J. (1985) Disturbance and patch dynamics of subtidal marine animals on hard substrata. In: *The ecology of natural disturbance and patch dynamics* (ed. by A. Pickett and S. White), pp. 125–151. Academic Press, Orlando, USA.
- Crooks, J.A. & Soulé, M.E. (1999) Lag times in population explosions of invasive species: causes and implications. In: *Invasive species and biodiversity management* (ed. by T. Sandlund, P.J. Schei and A. Viken), pp. 103–126. Kluwer Academic Publishers.
- EA (1999) *Australia's world heritage*. Department of Environment and Heritage, Commonwealth of Australia. (<http://ea.gov.au/heritage/awh/worldheritage> — Accessed: 13/01/2002).
- Elton, C.S. (1958) *The ecology of invasions by plants and animals*. Chapman & Hall, London.
- EPA (1998) *Construction of additional crystallisers: Useless Loop, Shark Bay*. Consultative Environmental Review, Environmental Protection Authority, Perth, Australia.
- Floerl, O. (2001) Loopholes for marine invaders. *Waves*, **8**, 1–2.
- Fowler, N. (1996) *Gascoyne aquaculture development plan*. Department of Fisheries and Gascoyne Development Commission, Perth, Australia.
- Fox, M.D. & Fox, B.J. (1986) The susceptibility of natural communities to invasion. In: *Ecology of biological invasions: an Australian perspective* (ed. by H. Broves and J. Burdon), pp. 57–66. Australian Academy of Science, Canberra, Australia.
- Furlani, D.M. (1996) *A guide to the introduced marine species in Australian waters*. Technical Report no. 5. Centre for Research on Introduced Marine Pests, CSIRO Marine Research, Hobart, Australia.
- Gili, J.-M., Hughes, R.G. & Alvà, V. (1996) Quantitative study of feeding by the hydroid of *Tubularia larynx* Ellis and Solander, 1786. *Scientia Marina*, **60**, 43–54.
- Glasby, T.M. (1999) Interactive effects of shading and proximity to the seafloor on the development of subtidal epibiotic assemblages. *Marine Ecology Progress Series*, **190**, 113–124.
- Glasby, T.M. & (in preparation) Unpublished manuscript.
- Grosholz, E. (2002) Ecological and evolutionary consequences of coastal invasions. *Trends in Ecology and Evolution*, **17**, 22–27.
- Hayes, K.R. & Sliwa, C. (2003) Identifying potential marine pests — a deductive approach applied to Australia. *Marine Pollution Bulletin*, **46**, 91–98.
- Hewitt, C.L. (2002) Distribution and biodiversity of Australian tropical marine bioinvasions. *Pacific Science*, **56**, 213–222.
- Hewitt, C.L. (2003) Marine biosecurity issues in the world oceans: global activities and Australian directions. *Ocean Yearbook*, **17**, 193–212.
- Hewitt, C.L., Campbell, M.L., Moore, K.M. & Murfet, N.B. (1997) *Introduced species survey of Bunbury, Western Australia*, CRIMP, CSIRO Division of Fisheries, Hobart, Tasmania.
- Hewitt, C.L., Campbell, M.L., Moore, K.M., Murfet, N.B. & McEnulty, F.R. (2000) *Introduced species survey of Fremantle, Western Australia*, CRIMP, CSIRO Division of Fisheries, Hobart, Tasmania.
- Hewitt, C.L., Campbell, M.L., Moore, K.M., Murfet, N.B. & Robertson, B. (1999a) *Introduced species survey of Port Hedland, Western Australia*, CRIMP, CSIRO Division of Fisheries, Hobart, Tasmania.
- Hewitt, C.L., Campbell, M.L., Thresher, R.E. & Martin, R.B. (1999b) *Marine biological invasions of Port Phillip Bay, Victoria*. Technical Report no. 20. Centre for Research on Introduced Marine Pests, CSIRO Marine Research, Hobart, Australia.
- Hewitt, C.L., Campbell, M.L., Thresher, R.E., Martin, R.B., Boyd, S., Cohen, B.F., Currie, D.R., Gomon, M.F., Keogh, M.J., Lewis, J.A., Lockett, M.M., Mays, N., McArthur, M.A., O'Hara, T.D., Poore, G.C.B., Ross, D.J., Storey, M.J., Watson, J.E. & Wilson, R.S. (2004) Introduced and cryptogenic species in Port Phillip Bay, Victoria, Australia. *Marine Biology*, **144**, 183–202.
- Hewitt, C.L. & Martin, R.B. (2001) *Revised protocols for baseline port surveys for introduced marine species: survey design, sampling protocols and specimen handling*. Technical Report no. 22, Centre for Research on Introduced Marine Pests, CSIRO Marine Research, Hobart, Australia.
- Hewitt, C.L., Martin, R.B., Sliwa, C., McEnulty, F.R., Murphy, N.E., Jones, T. & Cooper, S. (2002) *National introduced marine pest information system*. (<http://crimp.marine.csiro.au/nimpis> — Accessed: 03/05/2004).
- Hutchins, J.B. (1990) Fish survey of South Passage, Shark Bay, Western Australia. In: *Research in Shark Bay: report of the France-Australe bicentenary expedition committee* (ed. by P.F. Berry, S.D. Bradshaw and B.R. Wilson), pp. 263–278. Western Australian Museum, Perth, Australia.
- Jones, D.S. (1990) Annotated checklist of the marine decapod Crustacea of Shark Bay, Western Australia. In: *Research in Shark Bay: Report of the France-Australe bicentenary expedition committee* (ed. by P.F. Berry, S.D. Bradshaw and B.R. Wilson), pp. 169–208. Western Australian Museum, Perth, Australia.
- Kendrick, G.A., Huisman, J.M. & Walker, D.I. (1990) Benthic macroalgae of Shark Bay, Western Australia. *Botanica Marina*, **33**, 47–54.
- Largier, J.L., Hollibaugh, J.T. & Smith, S.V. (1997) Seasonally hypersaline estuaries in Mediterranean-climate regions. *Estuarine Coastal and Shelf Science*, **45**, 789–797.
- Lavoie, D.M., Smith, L.D. & Ruiz, G.M. (1999) The potential for intracoastal transfer of non-indigenous species in the ballast water of ships. *Estuarine Coastal and Shelf Science*, **48**, 551–564.
- Lewis, P.N. (2001) *In the wake of the Aurora: an investigation into the hazard of marine introductions in the Southern Ocean*. Unpublished Honours Thesis, University of Tasmania, Hobart, Australia.
- Lewis, P.N., Hewitt, C.L., Riddle, M. & McMinn, A. (2003) Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. *Marine Pollution Bulletin*, **46**, 213–223.
- Logan, B.W. & Cebulski, D.E. (1970) Sedimentary environments of Shark Bay, Western Australia. *American Association of Petroleum Geologists Memoirs*, **13**, 1–37.

- Logan, B.W., Davies, G.R., Read, J.R. & Cebulski, D.E. (1970) Carbonate sedimentation and environments in Shark Bay, Western Australia. *American Association of Petroleum Geologists Memoirs*, **13**, 205pp.
- Lyons, K.G. & Schwartz, M.W. (2001) Rare species loss alters ecosystem function — invasion resistance. *Ecology Letters*, **4**, 358–365.
- Marsh, L.M. (1990) Hermatypic corals of Shark Bay, Western Australia. In: *Research in Shark Bay: report of the France-Australe bicentenary expedition committee* (ed. by P.F. Berry, S.D. Bradshaw and B.R. Wilson), pp. 115–128. Western Australian Museum, Perth, Australia.
- McKinney, M.L. (1998) On predicting biotic homogenization: species-area patterns in marine biota. *Global Ecology and Biogeography*, **7**, 297–301.
- Nahas, E.L., Jackson, G., Pattiaratchi, C.B. & Ivey, G.N. (2003) Hydrodynamic modelling of snapper (*Pagrus auratus*) egg and larval dispersal in Shark Bay, Western Australia: reproductive isolation at a fine spatial scale. *Marine Ecology Progress Series*, **265**, 213–226.
- Olden, J.D., Poff, N.L., Douglas, M.R., Douglas, M.E. & Fausch, K.D. (2004) Ecological and evolutionary consequences of biotic homogenization. *Trends in Ecology and Evolution*, **19**, 18–24.
- Paulay, G., Kirkendale, L., Lambert, G. & Meyer, C. (2002) Anthropogenic biotic interchange in a coral reef ecosystem: a case study from Guam. *Pacific Science*, **56**, 403–422.
- Pollard, D.A. & Hutchings, P.A. (1990) A review of exotic marine organisms introduced to the Australian Region. 2. Invertebrates and algae. *Asian Fisheries Science*, **3**, 223–250.
- Rosenzweig, M.L. (2001) The four questions: what does the introduction of exotic species do to diversity? *Evolutionary Ecology Research*, **3**, 361–367.
- Ruiz, G.M., Carlton, J.T., Grosholz, E.D. & Hines, A.H. (1997) Global invasions of marine and estuarine habitats by non-indigenous species — mechanisms, extent, and consequences. *American Zoologist*, **37**, 621–632.
- Ruiz, G.M., Fofonoff, P.W., Carlton, J.T., Wonham, M.J. & Hines, A.H. (2000) Invasion of coastal marine communities in North America: Apparent patterns, processes, and biases. *Annual Review of Ecology and Systematics*, **31**, 481–531.
- Ruiz, G.M., Fofonoff, P., Hines, A.H. & Grosholz, E.D. (1999) Non-indigenous species as stressors in estuarine and marine communities: assessing invasion impacts and interactions. *Limnology and Oceanography*, **44**, 950–972.
- Shannon, C.E. & Weaver, W. (1949) *The mathematical theory of communication*. University of Illinois Press, Urbana.
- Shaw, J. (2000) *Fisheries environmental management review: Gascoyne region*. Fisheries Management Review no. 1. Fisheries Western Australia, Perth, Australia.
- Simberloff, D. (2000) No reserve is an island: marine reserves and non-indigenous species. *Bulletin of Marine Science*, **66**, 567–580.
- Simberloff, D. & Von Holle, B. (1999) Positive interactions of non-indigenous species: invasional meltdown? *Biological Invasions*, **1**, 21–32.
- Simpson, C.J., Colman, J.G. & Hill, A.K. (2002) *A strategic framework for marine research and monitoring in the Shark Bay World Heritage property*. Department of Conservation and Land Management, Perth, Australia.
- SKM (2001) *Marine pest species survey at Useless Loop*. Unpublished Report for Shark Bay Resources Pty. Ltd., Sinclair Knight Merz Pty. Ltd., Perth, Australia.
- SKM (2002) *Shark Bay resources Pty. Ltd. ballast water management plan*. Unpublished Report for Shark Bay Resources Pty. Ltd., Sinclair Knight Merz Pty. Ltd., Perth, Australia.
- Slack-Smith, S.M. (1990) The bivalves of Shark Bay, Western Australia. In: *Research in Shark Bay: report of the France-Australe bicentenary expedition committee* (ed. by P.F. Berry, S.D. Bradshaw and B.R. Wilson), pp. 129–143. Western Australian Museum, Perth.
- Sousa, W.P. (2001) Natural disturbance and the dynamics of marine benthic communities. In: *Marine community ecology* (ed. by M.D. Bertness, S.D. Gaines and M.E. Hay), pp. 85–130. Sinauer Associates, Sunderland, Massachusetts.
- Stachowicz, J.J., Whitlatch, R.B. & Osman, R.W. (1999) Species diversity and invasion resistance in a marine ecosystem. *Science*, **286**, 1577–1579.
- Sutherland, J.P. (1978) Functional roles of *Schizoporella* and *Styela* in the fouling community at Beaufort, North Carolina. *Ecology*, **59**, 257–264.
- Thresher, R.E. (1999) Diversity, impacts and options for managing invasive marine species in Australian waters. *Australian Journal of Environmental Management*, **6**, 137–148.
- UNESCO (1972) Convention concerning the protection of the world cultural and natural heritage. The General Conference of the United Nations Educational, Scientific and Cultural Organisation, Paris.
- Vermeij, G.J. (1991) When biotas meet: understanding biotic interchange. *Science*, **253**, 1099–1104.
- Walker, D.I. (1990) Seagrass in Shark Bay, Western Australia. In: *Research in Shark Bay: report of the France-Australe bicentenary expedition committee* (ed. by P.F. Berry, S.D. Bradshaw and B.R. Wilson), pp. 101–106. Western Australian Museum, Perth, Australia.
- Walker, D.I. & Woelkerling, W.J. (1988) Quantitative study of sediment contribution by epiphytic coralline red algae in seagrass meadows in Shark Bay, Western Australia. *Marine Ecology Progress Series*, **43**, 71–77.
- Wasson, K., Zabin, C.J., Bedinger, L., Diaz, M.C. & Pearse, J.S. (2001) Biological invasions of estuaries without international shipping: the importance of intraregional transport. *Biological Conservation*, **102**, 143–153.
- Wolanski, E. (1986) An evaporation-driven salinity maximum zone in Australian tropical estuaries. *Estuarine Coastal and Shelf Science*, **22**, 415–424.
- Wonham, M.J., Walton, W.C., Ruiz, G.M., Frese, A.M. & Galil, B.S. (2001) Going to the source: role of the invasion pathway in determining potential invaders. *Marine Ecology Progress Series*, **215**, 1–12.
- Wyatt, A.S.J. (2002) *The risk of marine introductions to the Shark Bay World Heritage property and its values*. Unpublished Honours Thesis, University of Western Australia, Perth, Australia.