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STATUS OF ESTUARINE AND MARINE NON-INDIGENOUS SPECIES IN SINGAPORE

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ABSTRACT. — The introduction of marine non-indigenous species is a global concern. Addressing the problem is made more challenging by the deficiency of data for non-indigenous estuarine and marine organisms, especially within Southeast Asia. In Singapore, three of the most important categories of marine invasion pathways are present: 1) shipping-related pathways, 2) commercial culture and fisheries, and 3) the ornamental trade. In this study, we conducted an exhaustive review to determine the status of and estuarine non-indigenous species in Singapore. A total of 17 non-indigenous species are established in estuarine and marine environments in Singapore. Commercially important non-indigenous species, which are imported for trade but are not known to be present in the environment, were also reviewed. We concluded by highlighting research directions aimed towards setting up a meaningful management framework for non-indigenous species.

KEY WORDS. — non-indigenous species, invasive species, marine, estuarine, introduction, Singapore

INTRODUCTION

Global systems are facing, with increasing frequency, the introduction of non-indigenous species through anthropogenic activities (Bax et al., 2001; Drake & Lodge, 2004; Semmens et al., 2004). While the introduction of non-indigenous species to terrestrial and freshwater systems has been relatively well documented, less is known of marine non-indigenous species (Coles & Eldredge, 2002; Molnar et al., 2008). Ironically, marine organisms have had a long history of being transported to new areas since vessels began sailing between regions (Carlton, 2009; Yeo et al., 2011). Anthropogenic introductions of marine non-indigenous organisms have been discussed as early as 1872 (Cooper, 1872 cited in Carlton, 2009). Yet, centuries later, scientists acknowledge the need for more information on the status of marine non-indigenous species in various marine eco-regions and their consequent impacts on native biota (Coles & Eldredge, 2002; Bax et al., 2003).

When considering anthropogenic pathways as modes of entry for marine non-indigenous species, countries with high vessel traffic and busy port areas appear to be at higher risk of marine biological invasions (Eldredge & Carlton, 2002; Eldredge & DeFelice, 2001). Singapore is a case in point, being an island city state, 137 km north of the equator, with a terrestrial area of 704 km^2. Situated at the southern tip of the Malay Peninsula between the Straits of Malacca and the South China Sea, Singapore is geographically primed as a convenient and logical port-of-call for regional as well as international shipping, including vessels travelling between the Indian and Pacific Oceans. Consequently, the island had been used as an international maritime port-of-call from as early as the 1300s (Miksic, 2000) although the modern trading port was established only in 1819 (as a British colony). Singapore is known as one of the world's busiest maritime hubs with 127,299 vessels (over 75 gross tonnes), calling at her port in 2010 alone (MPA, 2011). To accommodate the intense shipping activities, port waters cover a majority (82%) of Singapore's limited 600 km^2 marine territories (Chou, 2006).

The long maritime history and high intensity shipping activities of Singapore would have exposed its marine environments to elevated risks of marine biological invasions. However, while established non-indigenous species have been well documented in Singapore's terrestrial (Corlett, 1988; Turner & Tan, 1992; Ng et al., 1993; Lim & Gardner, 1997; Wee, 1997; Tan & Tan, 2000; Tan & Buck, 2002; Tan & Tan, 2003; Teo et al., 2003; Ng, 2009; Lok et al., 2010a, 2010b, 2010c) and freshwater (Ng & Lim, 2010; Ng & Tan, 2010; Yeo, 2010) environments, the historical records of marine counterparts are inadequate (Chou & Lam, 1989; Puthia et al., 2010). Chou & Lam (1989) listed the euryhaline Mozambique tilapia, *Oreochromis mossambicus*, as the only marine species that had established feral populations in Singapore in their review of aquatic non-indigenous species. This species was curiously omitted in the review on marine invasive species in Singapore in 2003 by Puthia et al. (2010), who only included three species: the Caribbean mussel *Mytilopsis sallei* and two species of dinoflagellates. This paper is a response to the call for a systematic review of the knowledge of non-indigenous marine species in Singapore (Chou & Lam, 1989; Yeo & Chia, 2010). In this review, we analyse published literature (including grey literature) as well as available unpublished data, to identify key estuarine and marine non-indigenous organisms found in Singapore, and highlight potential introductions and probable invasion pathways. We use the term 'non-indigenous species' to refer to species that have been simply introduced or spread beyond their native range as a result of human activities (Lodge et al., 2006). Alternative terms are 'exotic species', 'non-native species', or 'alien species'. Further, we define 'established non-indigenous species' as those that have formed self-sustaining populations. Our definitions used here do not allude to whether the species are harmful or cause negative impacts (i.e., invasive).

ESTUARINE AND MARINE NON-INDIGENOUS SPECIES

It is evident that some of the most important marine invasion pathways (Molnar et al., 2008) are prevalent in Singapore: shipping activities (which can be further divided into at least two distinct shipping-related pathways—bio-fouling on vessels and ballast water); commercial fisheries (again, further divided into two other distinct pathways—imported live seafood which are directly sold to the markets upon entry into Singapore, and those brought to Singapore in association with aquaculture and fisheries); and the ornamental pet/aquarium trade. For each invasion pathway, organisms reported as established in published literature are discussed. In addition, organisms cited in grey literature, inferred from published literature and the authors' unpublished data or personal observations are also included. In total, 17 non-indigenous species are established in estuarine and marine environments in the wild, including two bivalve molluscs, one polychaete worm, 12 fish species, and two species of dinoflagellates (Table 1). Fig. 1 illustrates the number of taxa introduced by the various invasion pathways. Numerous commercially important non-indigenous species, although not yet introduced into the environment, are frequently imported and/or cultured for the live seafood and ornamental trades, and are therefore covered in this review (Tables 2, 4, 5). Finally, a handful of non-indigenous species have been reported from bio-fouling surfaces on maritime vessels visiting Singapore (Table 3); these too are not known to be actually present in the environment.

Shipping activities. — Shipping hubs and ports such as Singapore are considered entry hotspots for marine non-indigenous species (Carlton, 1996; Hewitt, 2002; Hewitt et al., 2004). Each of the hundreds of thousands of vessels that call into such ports presents a potential source for introduction of a myriad of non-native organisms, which are transported by ballast water or hull fouling. Shipping-mediated invasion pathways including hull fouling and ballast water have been implicated in the arrival of six out of the 17 established marine non-indigenous species in Singapore (Table 1, Fig. 1).

The review on marine invasive species in Singapore by Puthia et al. (2010) presents data compiled in 2003, and appears to have only considered shipping-related activities as the invasion pathway. Only three species of established non-indigenous species were reported: the Caribbean mussel *Mytilopsis sallei*, and two species of dinoflagellates *Gymnodinium catenatum* and *Gymnodinium impudicum* (Holmes & Teo, 2002; Puthia et al., 2010). The latter two species are known only from temperate waters. The study by Holmes & Teo (2002) presented the first records of these species in Southeast Asia. Puthia et al. (2010) also included in their manuscript a ciguatoxin-producing dinoflagellate described from Singapore, *Gambierdiscus yasumotoi*, although there was no reason provided for its inclusion, and no discussion on its status as an invasive. As such, although *G. yasumotoi* was cited by Puthia et al. (2010), we have not included this species in the present list of established marine non-indigenous species.

The Caribbean mussel *Mytilopsis sallei* (Dreissenidae) is considered well-established in the tidal monsoon canals in Singapore (Tan & Chou, 2000). Forming dense mats along vertical and sloping concrete walls and floors of man-made canals, this species is now the dominant fouling organism within these communities (Tan & Morton, 2006). This

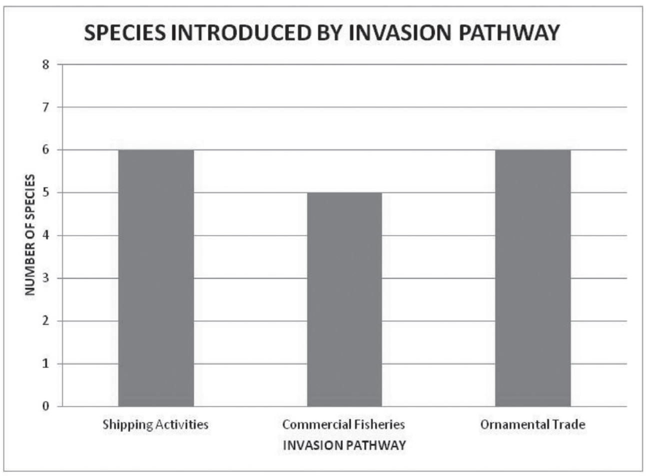

Fig. 1. Number of established non-indigenous species separated by invasion pathway.

Table 1. Established non-indigenous species in marine and estuarine environments in Singapore.

ORGANISM	FAMILY	SPECIES	ORIGIN/DISTRIBUTION	ROUTE	REFERENCE
DINOFLAGELLATES	Gymnodiniaceae	*Gymnodinium catenatum*	Temperate Waters	Shipping Activities	Holmes & Teo, 2002
		Gymnodinium impudicum	Temperate Waters	Shipping Activities	Holmes & Teo, 2002
MOLLUSCS	Dreissenidae	*Mytilopsis sallei*	Central America (Caribbean Sea)	Shipping Activities	Tan & Chou, 2000
	Mytilidate	*Brachidontes striatulus*	India	Shipping Activities	Morton & Tan, 2006
POLYCHAETES	Serpulidae	*Hydroides sanctaecrucis*	Central America (Caribbean Sea)	Shipping Activities	Lewis et al., 2006
FISH	Cichlidae	*Cichlosoma urophthalmus*	Central America	Ornamental Trade	Tan & Tan, 2003
		Cichlosoma urophthalmus × *Parachromis managuensis*	(hybrid)	Ornamental Trade	H. H. Tan, unpublished data
		Etroplus suratensis	Sri Lanka	Ornamental Trade	Ng and Tan, 2010
		Herichthys carpintis	Central America	Ornamental Trade	H. H. Tan, unpublished data
		Oreochromis aureus	Africa & Middle East	Commercial Fisheries	Smith et al., 1983
		Oreochromis mossambicus	East Africa	Commercial Fisheries	Harrison & Tham, 1973
		Oreochromis niloticus	Africa	Commercial Fisheries	Smith et al., 1983
		Veija spp.	Central America	Ornmental Trade	H. H. Tan, unpublished data
	Gobiidae	*Yongeichthys virgatulus*	Sagami Sea Japan	Shipping Activities	Z. Jaafar, unpublished data
	Poeciliidae	*Poecilia sphenops*	Central & South America	Ornmental Trade	Goh et al., 2002
	Scianidae	*Larimichthys crocea*	Northwest Pacific	Commercial Fisheries	K. K. P. Lim, unpublished data
		Sciaenops ocellatus	Western Atlantic	Commercial Fisheries	K. K. P. Lim, unpublished data

Table 2. Marine and estuarine species imported for mariculture.

ORGANISM	FAMILY	SPECIES	COMMON NAME	NATIVE DISTRIBUTION	REFERENCE
MOLLUSCS	Ostreidae	*Crassostrea gigas*	Pacific oyster	Indo-Pacific	Chou & Lee, 1997
	Mytilidae	*Perna viridis*	Asian green mussel	Indo-Pacific	Chou & Lee, 1997
CRUSTACEANS	Portunidae	*Scylla serrata*	mangrove mud-crab	Indo-West Pacific	Chou & Lee, 1997
	Palinuridae	*Panulirus polyphagus*	spiny lobster	Indo-West Pacific	Chou & Lee, 1997
	Penaeidae	*Fenneropenaeus merguiensis*	banana shrimp	Indo-West Pacific	Chou & Lee, 1997
		Penaeus monodon	tiger shrimp	Indo-West Pacific	Chou & Lam, 1989
FISH	Carangidae	*Alectis indicus*	threadfin trevally	Indo-Pacific	Chou & Lee, 1997
		Caranx ignobilis	yellowfin Jack	Indo-Pacific	Chou & Lee, 1997
		Gnathanodon speciosus	golden trevally	Eastern Indo-Pacific	Chou & Lee, 1997
		Trachinotus blochii	snubnose pompano	Indo-Pacific	Chou & Lee, 1997
	Chanidae	*Chanos chanos*	milkfish	Indo-Pacific	Ong, 2010
	Cichlidae	*Oreochromis nilaticus* × *aureus* × *mossambicus*	tilapia hybrid	Hybrid (Africa)	Pang, 2005
	Labridae	*Cheilinus undulatus*	hump headed wrasse	Indo-Pacific	Chou & Lee, 1997
	Latidae	*Lates calcarifer*	Asian seabass	Indo-West Pacific	Chou & Lee, 1997
	Lutjanidae	*Lutjanus argentimaculatus*	mangrove snapper	Indo-West Pacific	Chou & Lee, 1997
		Lutjanus johnii	golden snapper	Indo-West Pacific	Chou & Lee, 1997
	Mugilidae	*Mugil cephalus*	flathead grey mullet	Cosmopolitan	Ong, 2010
	Polynemidae	*Eleutheronema tetradactylum*	four-finger threadfin	Indo-West Pacific	Chou & Lee, 1997
	Rachycentridae	*Rachycentron canadum*	cobia	Western Pacific & Atlantic	AVA, 2011
	Serranidae	*Cromileptes altivelis*	polka-dot grouper	Western Pacific	Chou & Lee, 1997
		Ephinephelus malabaricus	Malabar grouper	Indo-Pacific	Chou & Lee, 1997
		Ephinephelus tauvina	estuarine grouper	Indo-Pacific	Chou & Lee, 1997
		Plectropomus leopardus	coral trout	Western Pacific	Chou & Lee, 1997
		Plectropomus maculatus	coral trout	Western Pacific	Chou & Lee, 1997
	Siganidae	*Siganus canliculatus*	seagrass rab	Indo-Pacific	Chou & Lee, 1997
		Siganus guttatus	gold-spotted rabbitfish	Western Pacific & Eastern Indian	Chou & Lee, 1997
		Siganus javus	streaked rabbitfish	Indo-Pacific	Chou & Lee, 1997
REPTILES	Crocodylidae	*Crocodylus porosus*	estuarine crocodile	Indo-Pacific	Chou & Lam, 1989

Table 3. Non-indigenous bio-fouling species collected from dry dock in Singapore (from Yeo et al., 2009).

ORGANISM	FAMILY	SPECIES	ORIGIN/DISTRIBUTION
BRACHYURAN CRABS	Pilumnidae	*Glabropilumnus seminudus*	East Indo-West Pacific
		Pilumnus cf. *schellenbergi*	Australia & New Guinea
		Pilumnus spinicarpus	Australia
	Portunidae	*Carupa tenuipes*	Indo-West Pacific
		Thalamitoides quaridens	Indo-West Pacific (oceanic)
	Xanthidae	*Chlorodiella laevissima*	Indo-West Pacific (oceanic)
		Liomera cinctimana	Indo-Pacific
		Liomera monticulosa	Indo-West Pacific (oceanic)
		Liomera rubra	Indo-West Pacific (oceanic)
		Liomera tristis	Indo-West Pacific (oceanic)
		Platypodia tomentosa	West Pacific
		Pseudoliomera helleri	Indo-West Pacific (oceanic)
		Xanthias punctatus	Indo-West Central Pacific
STOMATOPODS	Gonodactylidae	*Gonodactylaceus randalli*	West Pacific and Northern Australia (oceanic)

widespread species is believed to have been introduced through larvae transported in ballast water or adults attached to hulls of trans-oceanic vessels (Tan & Chou, 2000). Based on two specimens collected by D. H. Murphy from Mandai mangroves in May 1984, Tan & Morton (2006) postulated that this species was introduced into Singapore either in the 1950s or 1960s. Using mitochondrial cytochrome oxidase I (COI) data from established populations in Asia (including Singapore), Wong et al. (2010) were unable to determine the source region of the introduction of this species. They did, however, discover high haplotype diversity in Singapore, and suggested that the genetic variability present in the Singapore population was the result of multiple invasion events (Wong et al., 2010).

Another established non-indigenous species of bivalves, the Indian mussel, *Brachidontes striatulus* (Mytilidae), was found to also occur in man-made monsoon canals (Morton & Tan, 2006). Based on samples collected in Singapore, Morton & Tan (2006) suggested that, unlike *Mytilopsis sallei*, this species was introduced later, perhaps as recently as 2000. Found in more saline areas of the monsoon canals, this species occurred where *Mytilopsis sallei* were less abundant or absent. Morton & Tan (2006) further postulated that this species was introduced as larvae in ballast water from vessels originating from a harbor in the Bay of Bengal, India. The founding population is believed to have been introduced first into Rochor Canal and subsequently spread to Siglap Canal (see Morton & Tan, 2006). However, until population genetic studies are carried out, the possibility of two separate invasion events at these two locations cannot be discounted, especially considering the high frequency of vessels arriving in Singapore from the Bay of Bengal.

First collected from test pipes by S Teo and Y Cai in 2002, the polychaete keelworm *Hydroides sanctaecrucis* (Serpulidae) is presently well-established in fouling communities on artificial substrates around Singapore and it is believed to have been transported via fouling on hulls of trans-oceanic vessels (Lewis et al., 2006). This species was first described from the Lesser Antilles in the Caribbean Sea and has been recorded from the Atlantic Ocean (Bastida-Zavala & ten Hove, 2003a) and from parts of the Pacific Ocean in Panama (Bastida-Zavala & ten Hove, 2003b). It is known to be an invasive species in Hawaii (Long, 1974) and Australia (Lewis et al., 2006).

The East Asian gobiid fish species, *Yongeichthys virgatulus* was first collected in Singapore in 1994 from the sub-littoral zone of Changi Beach, on the eastern end of the main island (Jaafar et al., in prep.). Given the history of intensive and extensive sampling and resulting good historical representation of estuarine fishes in Singapore (Cantor, 1850; Tham, 1973; Lim & Low, 1998; Larson et al., 2008) in both local as well as international museums (Fowler, 1931; Tweedie, 1936, 1940), this species is unlikely to have been present in Singapore prior to 1994 as an undiscovered cryptic native species. Since 1994, additional specimens of *Y. virgatulus* have been collected from various sites around mainland Singapore as well as from southern offshore islands

Table 4. Marine and estuarine species imported for the live seafood trade.

ORGANISM	FAMILY	SPECIES	IMPORT SOURCE	REFERENCE
MOLLUSC BIVALVES	Arcidae	*Anadara granosa*	Southeast Asia	Z. Jaafar, unpublished data
	Corbiculidae	*Geloina* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Cultellidae	*Siliqua* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Glauconomidae	*Glauconome* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Hiatellidae	*Panopea* spp.	USA	Z. Jaafar, unpublished data
	Mytilidae	*Perna* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Ostreidae	*Crassostrea* spp.	Australia, New Zealand	S. K. Tan, unpublished data
		Saccostrea spp.	Australia, New Zealand	Z. Jaafar, unpublished data
	Pectinidae	*Amusium* spp.	Southeast Asia	Z. Jaafar, unpublished data
		Chlamys spp.	Southeast Asia	Z. Jaafar, unpublished data
	Pharidae	*Orbicularia* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Pinnidae	*Pinna* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Veneridae	*Paphia* spp.	Southeast Asia	Z. Jaafar, unpublished data
MOLLUSC GASTROPODS	Strombidae	*Lambis lambis*	Southeast Asia	Z. Jaafar, unpublished data
		Strombus canarium	Southeast Asia	Z. Jaafar, unpublished data
	Trochidae	*Trochus* spp.	Southeast Asia	Z. Jaafar, unpublished data
	Volutidae	*Cymbiola nobilis*	Asia	Z. Jaafar, unpublished data
		Melo spp.	Asia	Z. Jaafar, unpublished data
CRUSTACEAN SHRIMPS	Penaeidae	*Fenneropenaeus merguiensis*	Southeast Asia	Yeo et al., 2011
		Litopaneus vannamei	Southeast Asia	Yeo et al., 2011
		Panaeus monodon	Southeast Asia	Yeo et al., 2011
CRUSTACEAN LOBSTERS/ SLIPPER LOBSTERS	Nephropidae	*Homarus americanus*	Northeastern America	Yeo et al., 2011
	Palinuridae	*Jasus edwardsii*	Australia	Yeo et al., 2011
		Panulirus femoristriga	Southeast Asia	Yeo et al., 2011
		Panulirus homarus	Southeast Asia	Yeo et al., 2011
		Panulirus longipes	Southeast Asia	Yeo et al., 2011
		Panulirus ornatus	Southeast Asia	Yeo et al., 2011
	Scyllaridae	*Parribacus antarcticus*	Southeast Asia	Yeo et al., 2011
		Scyllarides haanii	China, Philippines	Yeo et al., 2011
CRUSTACEAN ANOMURAN CRABS	Lithodidae	*Paralithodes camtschaticus*	Japan, Russia	Yeo et al., 2011

Table 4. Cont'd.

ORGANISM	FAMILY	SPECIES	IMPORT SOURCE	REFERENCE
CRUSTACEAN CRABS	Cancridae	*Cancer pagurus*	Scotland	Yeo et al., 2011
		Metacarcinus magister	Northeastern Pacific (Canda)	Yeo et al., 2011
	Geryonidae	*Chaceon albus*	Western Australia	Yeo et al., 2011
	Menippidae	*Pseudocarcinus gigas*	Western Australia	Yeo et al., 2011
	Hypothalassidae	*Hypothalassia acerba*	Western Australia	Yeo et al., 2011
	Portunidae	*Scylla paramamosain*	Southeast Asia, Southeast China	Yeo et al., 2011
		Scylla olivacea	Southeast Asia	Yeo et al., 2011
		Scylla serrata	Southeast Asia, Australia	Yeo et al., 2011
		Scylla tranquebarica	Southeast Asia	Yeo et al., 2011
	Varunidae	*Eriocheir hepuensis*	China	Yeo et al., 2011
		Eriocheir sinensis	China	Yeo et al., 2011
CRUSTACEAN STOMATOPODS	Lysioqullidae	*Lysiosquilla maculata*	Malaysia, Indonesia	Yeo et al., 2011
	Squillidae	*Harpiosquilla raphidea*	Sabah, Indonesia	Yeo et al., 2011
CARTILIGENOUS FISH	Carcharhinidae	*Carcharhinus melanopterus*	Southeast Asia	Z. Jaafar, unpublished data
BONY FISH	Cichlidae	*Oreochromis niloticus*	Local Suppliers, Southeast Asia	Z. Jaafar, unpublished data
	Labridae	*Cheilinus unulatus*	Southeast Asia	Z. Jaafar, unpublished data
	Latidae	*Lates calcarifer*	Local Suppliers, Southeast Asia	Z. Jaafar, unpublished data
	Rachycentridae	*Rachycentron canadum*	Local Suppliers, Southeast Asia	Z. Jaafar, unpublished data
	Serranidae	*Cromileptes altivelis*	Southeast Asia	Z. Jaafar, unpublished data
		Ephinephelus coioides	Southeast Asia	Z. Jaafar, unpublished data
		Ephinephelus malabaricus	Local Suppliers, Southeast Asia	Z. Jaafar, unpublished data
		Ephinephelus tauvina	Local Suppliers, Southeast Asia	Z. Jaafar, unpublished data
		Plectropomus leopardus	Local Suppliers, Asia	Z. Jaafar, unpublished data
		Plectropomus maculatus	Local Suppliers, Asia	Z. Jaafar, unpublished data
	Siganidae	*Siganus canaliculatus*	Southeast Asia	Z. Jaafar, unpublished data
		Siganus guttatus	Southeast Asia	Z. Jaafar, unpublished data
		Siganus javus	Southeast Asia	Z. Jaafar, unpublished data
	Soleidae	unident.	France	Z. Jaafar, unpublished data

Table 5. Marine and estuarine species common in the ornamental trade (Z. Jaafar, unpublished data).

ORGANISM	FAMILY	REMARKS
CNIDARIANS	Various stony corals	*Acropora* and *Fungia* are popular
	Various soft corals	*Dendronephthya* spp. are popular
	Various anemones	Symbionts of anemonefishes are popular
MOLLUSCS	Conidae	Various species
	Cypraeidae	Various species
	Pectinidae	*Chlamys* spp.
	Tridacnidae	All species equally popular
	Trochidae	*Trochus* spp.
ECHINODERMS	Ophidiasteridae	*Linckia* spp.
POLYCHAETES	Sabellidae	Various species
CRUSTACEANS	Alpheidae	Symbionts of gobiid fishes are popular
	Hippolytidae	*Lysmata* spp.
	Stenopodidae	*Stenopus* spp.
FISH	Pomacentridae	Anemonefishes especially popular
	Chaetodontidae	Various species
	Acanthuridae	Various species
	Scorpaeneidae	Pteroniid especially popular
	Balistidae	Various species
	Labridae	Cleaner wrasses & smaller species are popular
	Gobiidae	Various species
	Pomacanthidae	Various species
	Callionymidae	Various species
	Syngnathidae	*Hippocampus* spp.

such as Pulau [=Island in Malay] Hantu and Pulau Semakau. This species was described from Sagami Sea in Japan, and has not been recorded elsewhere. However, its sister species, *Yongeichthys pflaumii* (reported as *Acentrogobius virgatulus*), also described from Japan, had been reported as invasive in Australia (Lockett & Gomon, 2001) and New Zealand (Francis et al., 2003). It is the opinion of the authors that *Y. virgatulus* was most likely transported to Singapore as larvae in ballast water of vessels from Japan.

The six taxa mentioned above represent the only confirmed established non-indigenous estuarine and marine species in Singapore currently believed to be associated with shipping pathways. Two recent studies of fouling communities of artificial structures in Singapore waters, however, included several new records of marine algae and sponges that are potentially introduced by shipping (Lee et al., 2009; Lim et al., 2009). Lim et al. (2009) studied sponges from fouling communities of navigational buoys along the coast of Singapore and found eight new records. While these sponges appear to have a tropical Indo-Pacific distribution, some of the new records, e.g., *Prosuberites oleteira* described from Hawaii, show a greatly increased distribution, and this is the first record in Southeast Asia (Lim et al., 2009). Similarly, Lee et al. (2009) found 38 new records of marine algae on intertidal reef flats, artificial structures, and artificial navigation buoys located along the coast of Singapore. This included 11 species not previously known even from Southeast Asia such as *Gracilaria corticata* and *Chrysymenia procumbens* (Lee et al., 2009). Based on great expansions in distribution, together with the occurrence of singletons or just a few specimens, the authors suspected that some of these new algae and sponge records may in fact represent introduced species. However, until their statuses can be ascertained, we choose not to include any of these species in our present list of established non-indigenous species (Table 1).

In addition to traditional shipping, heavily-fouled navigation buoys, floating docks, and floating oil rigs are also very high risk vectors of anthropogenic introduction. These structures often lack anti-fouling treatment, spend extended periods stationary, are towed very slowly over great distances, and are cleaned at shallow water areas. The above factors may allow for easy dispersal of fouling organisms (Yeo et al., 2009; Carlton, 2001). This was illustrated by a sampling of decapods crustaceans from a semi-submersible oil platform being cleaned at a dry dock in Singapore, which yielded 14 non-indigenous species—13 species of crabs and one species of mantis shrimp (Yeo et al., 2009) (see Table 3). The non-indigenous species comprised more than 70% of the abundance of all decapod crustacean specimens collected. One species of mantis shrimp, *Gonodactylaceus randalli* (Stomatopoda) was not only a new record to the area, but also represented the first time that a stomatopod crustacean was identified to be present within a bio-fouling community on a moving structure (Yeo et al., 2009). In addition, some female specimens of the portunid crab *Carupa tenuipes,* a known invasive crab species in Hawaii, were found to be ovigerous (Yeo et al., 2009). While none of these species had been encountered on natural or artificial surfaces in the estuarine or marine environment in Singapore, the potential invasive threat was nevertheless regarded as high (Yeo et al., 2009).

Leisure crafts travelling in shallower waters and/or nearer to habitats of high biodiversity, and hence, high ecological and conservation value, such as coral reefs, seagrass beds, and mangroves, are also important vectors of introduction. These vessels dock more frequently than larger ships and navigate areas with more hospitable conditions, thus increasing viability of fouling organisms (Carlton, 2001). Singapore is at high risk for this type of invasion pathway as it is located within an archipelago where the surrounding waters are shallow and many large and small ferries, as well as leisure crafts, cruise from island to island. In 2010 alone, 31,739 passenger vessels and regional ferries (over 75 gross tonnes) called into Singapore's ports (MPA, 2011) while the many more vessels falling short of this tonnage were not even considered in the census. As more marinas and cruise centers are constructed to attract high-income tourism and water-front living, and to accommodate the increasing demands for docking points, more leisure crafts will be expected to traverse our coastlines from neighbouring regions (Jaafar, 2001). The smaller vessels should be considered when assessing threats of marine non-indigenous species.

Commercial fisheries. — The trans-location of non-native organisms to new locales as food is by no means a recent phenomenon. The culture of marine organisms for food has been acknowledged as one of the major pathways for introduction of non-indigenous species (Crossman & Cudmore, 1999; Carlton, 2001). The incidences of deliberate as well as unintentional releases are high, especially when organisms are cultured in sea pens and net cages. Endo- or epi-biotic organisms on non-native organisms in sea-pens and cages (Yeo et al, 2011) or diseases (Ong, 2010) can still be introduced into the environment. Escaped organisms can often tolerate or even thrive in local conditions, a reason for their culture in the first place, and feral populations are able to establish. Singapore has 95 coastal floating fish farms and 16 deep sea farms, hatcheries, and oyster and shellfish farms that currently produce 4% of the country's total fish (including crustaceans and shellfishes) consumption (Agri-Food & Veterinary Authority of Singapore (AVA), 2011a). Currently, AVA is aiding these farms in order to increase their production and to meet a target of 15% of Singapore's total fish consumption (AVA, 2011a). For marine finfish, hatchlings and fingerlings are mostly purchased from neighbouring countries such as Malaysia, Indonesia, Thailand, and Taiwan (Chou & Lee 1997; Oi, 2010; AVA, 2011b; Lim, 2011). The fishes are then grown in various facilities around Singapore and sold at the appropriate weight (Chou & Lee 1997; Oi, 2010; Lim 2011). These fishes include various species of groupers, trevallies, and snappers (see Table 2). Spat of shellfish species such as the green mussel, *Perna viridis*, are harvested from the wild locally but stocks are also supplemented by sub-adults imported from neighbouring countries (Jaafar Z., pers. obs.). The Pacific Oyster, *Crassostrea gigas*, is brought in from Australia and grown in a floating farm off the eastern coast of Singapore. The oysters are supposedly chemically sterilised prior to being shipped to Singapore (Tan S. K., pers. comm.). Young of crustaceans reared in local farms are also purchased from neighbouring countries (Chou & Lee, 1997). All of these organisms are grown to desired sizes before being sold in the local market. As the distribution of these species are often within the Indo-Pacific, it is difficult to ascertain if fishes found in natural habitats here are native or from feral populations, made up of escapees from fish farms. Incidences of escaped organisms are known (Lin & Lim, 2011) but it is believed that since Singapore is within the natural distribution of these species, the ecological impact of escapees would be minimal, if any (Chou & Lam, 1989). Conversely, feral populations originating from fish species not native to the region are more likely to be potentially invasive. The red drum, *Sciaenops ocellatus* (western Atlantic), and the yellow croaker, *Lamirichthys crocea* (northwest Pacific), are examples of fish species which were introduced for mariculture but that have escaped (or been released) and established feral populations in coastal waters of Singapore (Lim K. K. P., pers. comm.).

Tilapias, also known as the 'aquatic chicken' (ICLARM, 1984) due to the ease and speed at which these fishes grow, are one of the most important groups of fishes subjected to intensive mariculture. Though naturally distributed in East Africa, *Oreochromis mossambicus* was introduced to Singapore as a commercial food fish from a population already present in Java, Indonesia during the Japanese occupation of Singapore in 1942–1945 (World War II) (Harrison & Tham, 1973). It is believed that *O. mossambicus* was brought into Asia prior to the 1950s as a solution to the short supply of protein (Lin, 1977). However, overcrowding in small ponds led to stunting in this species (Smith & Pullin, 1984). This was presumably the reason why another two species which were believed to have better yield (*O. niloticus* and *O. aureus*) were introduced. The original distributions of these two species are Africa, and Northwestern Africa to the Middle East respectively, although the origins of the populations introduced to Singapore are unknown. What is certain is that by the mid to late 1970s, these two species were present and cultured in Singapore (Smith et al., 1983). Upon establishing viable commercial populations in Singapore, *O. aureus* and *O. mossambicus* were introduced to the Philippines and Hong Kong respectively (De Silva et al., 2004). There were also efforts for a tri-hybrid between *O. niloticus-aureus* and *O. mossambicus* to be stocked in the coastal fish farms (Pang, 2005). Tilapine cichlid fishes, such as these species, are known to be robust and are usually able to tolerate wide salinity ranges (Payne, 1983). At present, these species (listed in Table 1), including tilapine hybrids, have naturalised and are frequently encountered in many estuarine habitats.

Singapore is the largest consumer per capita of live seafood in Southeast Asia with supplies mostly originating from Indonesia (Bentley, 1999; Koeshendrajana & Hartono, 2006). There are some risks associated with organisms in the live seafood trade escaping or being released to the wild (Everett, 2000; Yeo et al., 2011). The extensive variety of organisms imported for the live seafood trade is dependent on supplies and is therefore difficult to list exhaustively. However, we include the more frequently encountered species in the trade, including the marine decapods and stomatopod species listed by Yeo et al. (2011) in Table 4.

Ornamental (aquarium) trade. — The ornamental (i.e., all marine organisms traded for marine aquaria) trade is a recognised pathway for the accidental introduction of non-indigenous organisms to natural habitats (Whitfield et al., 2002; Semmens et al., 2004). The ornamental trade is a major industry in Singapore, with export value of almost 100 million Singapore dollars in 2008 (Ministry of National Development, 2009). While most of the ornamental organisms are freshwater species that are imported from all over the world or cultured locally, most of the marine organisms are wild-caught and imported from countries such as Indonesia, Philippines, India, and Sri Lanka (Wabnitz et al., 2003; Yeo et al., 2011). Cichlids are popular aquarium fishes, and some of these fishes have been introduced to natural environments in Singapore. The Mayan cichlid, *Cichlosoma urophthalmus*, and the green chromide, *Etroplus suratensis*, have both established populations in estuarine rivers and coastal areas in Singapore (Tan & Tan, 2003). The former species is a sought-after aquarium species originating from Central America (Tan & Tan, 2003). The latter species is native to Sri Lanka and southern India but has been introduced to countries such as Malaysia (Lever, 1996). First collected from the wild in Singapore in 1995, *Etroplus suratensis* is believed to be most likely introduced to the natural environment through accidental or deliberate release of aquarium specimens (Ng & Tan, 2010). However, Ng & Tan (2010) also considered the possibility that this species might have spread naturally from Malaysian waters into Singapore. Another species, the pearlscale cichlid, *Heriichthys carpintis*, had been observed in brackish waters at Sungei Buloh Wetland Reserve in northern Singapore, with the first specimen collected in November 2007 (Fig. 2). As this species is common in the aquarium trade, we believe this to be the pathway of introduction. Ornamental hybrid cichlids have also been observed and collected from brackish-water areas. There were several records of the flower horns, escaped or released hybrids of *Veija*, in brackish water areas in the early 2000s, which were extremely popular in the ornamental fish trade at that time. Other cichline hybrids such as *Parachromis managuensis* × *Cichlasoma urophthalmus* have also been collected from brackish areas of Sungei Buloh Wetland Reserve (Fig. 3). The common molly, *Poecilia sphenops* (Poeciliidae), originally from Central and South America, was also introduced for the aquarium trade, and typically sold as live food for predatory fishes (Goh et al., 2002). This species is now one of the most common fishes in estuarine canals and mangrove streams (Lim & Low, 1998).

In a paper on the introduction of exotic aquatic species in Singapore, Chou & Lam (1989) listed six fish families that were available in the aquarium trade: Pomacentridae (damselfishes and anemonefishes), Chaetodontidae (butterflyfishes), Acanthuridae (tangs and surgeonfishes), Scorpaeneidae (peacock lionfishes), Balistidae (triggerfishes), and Labridae (wrasses). Due to the increased popularity of the marine aquarium trade in the past decade, thousands of species of marine organisms are now traded, predominantly originating from Southeast Asia (Wabnitz et al., 2003). Unfortunately, this trade is at present not sustainable, as almost all organisms are wild caught (Wabnitz et al., 2003). The marine aquaria hobby is popular in Singapore with many aquarium suppliers trading in a variety of marine organisms including fishes, molluscs, echinoderms, cnidarians, and crustaceans. Availability of organisms is dependent on supplies from the various locations and difficult to list. However, in table 5, we include several of the more popular groups often encountered in the trade, including the marine decapod and stomatopod species listed by Yeo et al. (2011).

DISCUSSION

Several factors contribute to difficulties in determining the presence of non-indigenous species in Singapore. The lack of historical baseline of native organisms in Singapore and the surrounding Southeast Asian region is a major problem. The number of established marine non-indigenous species in Singapore is low despite the constant and high propagule pressure from three main invasion pathways: shipping activities, commercial fisheries, and marine ornamental trade. Anthropogenic influence, however, is not restricted

Fig. 2. *Heriichthys carpintis*, collected from Sungei Buloh Wetland Reserve in Nov.2007.

Fig. 3. Hybrid of *Parachromis managuensis* × *Cichlasoma urophthalmus* collected from Sungei Buloh Wetland Reserve in Nov.2007.

to just these pathways. The beliefs and lifestyles of some Singaporeans also enhance the likelihood of non-indigenous organism introduction and dispersal, especially for easily obtainable species entering the country via commercial fisheries and marine ornamental trade. Buddhists in Singapore engage in mercy releases during Vesak Day where organisms are often released into the wild for spiritual merit (Ng 2009; Yeo & Chia, 2010). With the vast array of organisms easily available in the aquarium trade, releasing non-indigenous organisms into the marine environment is not uncommon. There have also been incidences of fishes and invertebrates being purchased from the live seafood trade to be released for spiritual merit as well as for other purposes, such as well-intentioned but poorly planned 'enhancement' of the biodiversity or aesthetics of the environment. One incident in the early 2000s involved a group of divers from SeaHound SCUBA releasing aquarium-purchased sharks and other large fishes into coastal reefs off Singapore's southern islands (Jaafar Z., pers. obs.). It is not known if these sharks were native or if their release affected the community structure of the coral reefs where they were released. In a review of various pathways of invasion, Carlton (2001) also cited the propensity of introductions inadvertently through the movement of SCUBA gear. In these instances, small marine organisms lodged in buoyancy devices may be transferred from one dive site to another. In Singapore alone, there are at least 200,000 certified divers (data from 15 largest SCUBA-diving companies in Singapore, courtesy of J. C. P. Ng, 2011). With such a large number of SCUBA divers in Singapore in recent years, and the proximity of recreational dive sites throughout the region, this is not an unrealistic mode of translocation of marine organisms.

The low incidence of established non-indigenous organisms in estuarine and marine environments of Singapore is not unique. Similar patterns have been observed in ports in tropical Australia (Hutchings et al., 2002). Areas further from the equator, such as ports in southern Australia and New Zealand (Hutchings et al., 2002) as well as those in Hawaii (Eldredge & DeFelice, 2001; Coles & Eldredge, 2002; Eldredge & Carlton, 2002), however, appear to harbour a higher number of introduced organisms. The paucity of baseline data owing to the lack of taxonomic expertise and research funds have often been cited as a primary reason for this pattern (Yeo & Chia, 2010). Hutchings et al (2002), however, argued that the lower incidences of invasive organisms in tropical seas is not a function of a smaller number of studies, but rather that, the tropical marine ecosystems with higher diversity, and more inter-specific competition and complex community interactions, are more resilient to introductions (Hatcher et al., 1989; Hutchings et al., 2002). Consequently, introduced organisms are presented with fewer opportunities to occupy and compete on arrival in novel areas (Hutchings et al., 2002).

The situation in Singapore probably lies somewhere in between these two scenarios. Singapore is privileged in having a strong history in marine research, although the data has bias towards larger marine organisms such as fishes, crustaceans, echinoderms, and molluscs. While there have been few extensive studies on taxonomically-difficult and sessile taxa such as polychaetes, cnidarians, and bryzoans, other reports yield low to no non-indigenous species (e.g., see list of echinoderms by Lane & Vandenspiegel, 2003). With the exception of the two species of non-native dinoflagellate protists recorded (Holmes & Teo, 2002; Puthia et al., 2010), there exists no further published records of non-native marine micro-organisms. Singapore's exposure to three major marine non-native introduction pathways has strong implications for her native flora and fauna. For a country such as Singapore with vested interest in preserving native biodiversity, the responsible way forward would be to improve the knowledge of marine introductions (Chou & Lam, 1989; Yeo et al., 2011). As the utility of risk assessment tools decreases with decreasing taxonomic resolution, more thorough documentation of marine resources is needed to plug current knowledge gaps. Investment in taxonomic expertise is essential, and potential cryptogenic species must be investigated. The potential ecological impacts of known non-indigenous organisms must be studied as must the effects of any parasites or diseases introduced with them.

To date, there is no quantitative data on the relative or specific importance of each of the major invasion pathways in tropical Southeast Asia. The identification of invasion pathways of most of the established organisms is largely based on anecdotal or circumstantial evidence. Evaluating the risk of introduction events through understanding of the various invasion pathways is an important objective. To this end, identifying taxa that are transported by the major invasion pathways, as well as the traits that enhance their affinity for the various pathways, may also prove useful. Information from these exercises, as well as those mentioned earlier, can serve to inform appropriate pathway-specific management plans for Singapore. It is hoped that this review can help to provide a primer for a meaningful framework for future legislation and effective management of our estuarine and marine resources with respect to non-indigenous species issues.

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