Assessing likelihoods of marine pest introductions in Sydney estuaries: A transport vector approach

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EXECUTIVE SUMMARY

Pest species are often stated to be some of the greatest global threats to native biodiversity. There are currently five nationally-listed, and internationally recognised, marine pests in NSW, with a further five established in other states. These species and numerous potential marine pests, not yet found in Australia, have been included on a national "trigger list" and these will be the main focus of the Commonwealth's proposed pest surveys of all major Australian commercial ports. A crucial factor in being able to eradicate or control any pest is early detection. Given the large costs involved in monitoring for marine pests, and limited resources, it is essential that we have a better understanding of which pests are most likely to invade a port, such that sampling can be targeted to detect these species. Moreover, it would be naïve to assume that the next major marine pest in Australia will be one of the species on any national list.

This project was designed to investigate the feasibility and applicability of using a transport vector approach for assessing the likelihood of marine pest introductions in NSW. As such, the project focussed on Sydney estuaries with the intention that, if successful, it could be extended to include all NSW estuaries. To this end, we have not considered transport of pests from Port Jackson, Botany Bay or Port Hacking to other NSW estuaries, nor arrival of new international pests to a non-Sydney port and subsequent transport to the three Sydney estuaries.

The specific objectives of this project were to:

1. Identify the international ports that are most likely to be the source of any marine species that could be introduced to Port Jackson or Botany Bay and become a pest (based on environmental similarity of the ports and amount of connectivity).
2. Identify which of the 29 nationally-listed marine pests, plus the New Zealand green lip mussel, *Perna canalicilus*, could survive and reproduce in Port Jackson, Botany Bay or Port Hacking (based on temperature and salinity tolerances only).
3. Of these species, identify which are the most likely to be introduced into Port Jackson or Botany Bay via international shipping and boating connections.
4. Determine the likelihood that any of the marine pests already in Australia could be transported to Port Jackson, Botany Bay or Port Hacking.

Likelihoods of introduction were calculated using data on degree of connectivity among ports or estuaries by different vectors. We also considered the likelihood that particular species would be transported by each vector. The international vectors that were considered were commercial shipping and recreational boating. Domestic vectors included commercial shipping, recreational boating, oyster aquaculture stock movements, commercial fishing vessels, and oceanic currents. In some respects this study was not a true risk assessment because we did not consider the consequences of invasion for each marine pest (risk is typically calculated as likelihood × consequence), only the likelihood of each species arriving. But we made the conservative, and arguably realistic, assumption that the invasion of any pest could have severe consequences and it is almost impossible to predict what those consequences might be. Furthermore, because we have based our assessment on a pre-defined list of potential marine pests (i.e., the national trigger list), we consider that we are, by default, considering species that will have unwanted consequences if they were to invade and establish. Thus, consequence is considered the same for each pest species, meaning that likelihood is directly proportional to risk. Hence we have used the terms likelihood and risk synonymously throughout this report.

Environmental matching of international ports and Sydney ports using temperature and salinity data identified numerous ports that were similar to, and had some shipping connection with, Botany Bay or Port Jackson. When total numbers of connections with each port were taken into account, Botany Bay was found to be at more risk of invasion than was Port Jackson, with the ports of Shanghai, Hong Kong and Auckland ranking as the most likely sources of a new pest for Botany Bay. The environmental matching did not take into account the presence of any known pests, but rather assumed that, if the environments are similar, there is a reasonable chance that a marine species (either native or introduced) living in the ports of Shanghai, Hong Kong or Auckland could also live in Botany Bay. The next most risky ports based on environmental similarity and numbers of connections with Botany Bay are Pusan (Korea), Kaohsiung (Taiwan), Tauranga (New Zealand) and Lyttelton (New Zealand). The most likely sources of a new pest for Port Jackson are Singapore, Auckland, Port Vila, Nouméa, Tauranga or Napier, but their likelihoods are less than for any of the aforementioned ports for Botany Bay.

Of the 30 marine pests of concern considered in this assessment, the Asian bag (or date) mussel *Musculista senhousia* is, based on the number of vector connections, the most likely to arrive here from overseas. *M. senhousia* is considerably more likely to be transported from an international port to Botany Bay than to Port Jackson. The Asian bag mussel is not known to occur in NSW, but has invaded estuaries in Victoria, South Australia, Tasmania and Western Australia. For this reason, *M. senhousia* is also likely to arrive in Botany Bay or Port Jackson from a domestic port. Although *M. senhousia* was not identified as a risk for Port Hacking (because there are no known connections between Port Hacking and another port that has *M. senhousia*), the connectivity we identified among Sydney estuaries means that any invasion of Botany Bay or Port Jackson could pose a significant secondary risk to Port Hacking. *M. senhousia* can cause significant ecological impacts by smothering benthic sediments, thereby excluding native invertebrates and potentially affecting the growth of seagrass beds, in addition to fouling infrastructure.

Of the next 11 most highly ranked pests that could arrive in Botany Bay from overseas ports, eight are not yet in Australia. Of these, the Asian clam, *Potamocorbula amurensis*, is the second most likely to arrive here after *M. senhousia*, and is also a greater risk for Botany Bay than for Port Jackson. *P. amurensis* is ranked as one of the most threatening marine pests in the world and could have serious impacts on sediments and native invertebrates, or alter natural fluctuations in phytoplankton abundance. The other marine pests not yet in Australia that rank highly as potential invaders of Botany Bay, based on number of vector connections, include three crab species (*Hemigrapsus takanoi*, *Hemigrapsus sanguineus*, *Charybdis japonica*), the black-striped mussel *Mytilopsis sallei* (which invaded Darwin ports in 1999 but was eradicated), the brown seaweed *Sargassum muticum*, and the whelk *Rapana venosa*. Some of these species would, however, only pose a threat to Sydney estuaries if they arrived in the cooler months, but could then potentially be transported to estuaries further south where long-term survival is more likely.

The port of Melbourne is by far the most likely origin for a domestic marine pest invasion, ranking higher for Botany Bay than for Port Jackson. There are seven significant marine pests currently in Melbourne, four of which have not been recorded in NSW, and only one of which (*Codium fragile* ssp. *tomentosoides*) is known to be present in Sydney ports.

Considering international and domestic connections in combination, the next most likely invaders are the northern Pacific seastar, *Asterias amurensis* (most likely to invade Botany Bay), the European green shore crab, *Carcinus maenas* (equally likely to invade Botany Bay or Port Jackson), and the Japanese kelp *Undaria pinnatifida* (more chance of invading Botany Bay, but also a high risk for Port Jackson). All of these species have already invaded Australia, and the green shore crab has been recorded recently from nine estuaries or lakes in southern NSW, the most northerly being Batemans Bay. There are historical records of the green shore crab for Port Jackson in the early 1900s and for Botany Bay as recently as 1987. The likelihoods of pests invading each target estuary were calculated without using data on the current status of pests in that target estuary. So the fact that this assessment identified as high risk a pest that has previously been recorded in Port Jackson and Botany Bay, plus two other pests that are already present in all three

Sydney estuaries (*Codium fragile* ssp. *tomentosoides* and *Caulerpa taxifolia*) indicates that the methodology used was appropriate.

In summary, this assessment has identified the international and domestic ports that are currently the most likely sources for marine pest incursions for Port Jackson, Botany Bay and Port Hacking. It has also identified which of the nationally-listed marine pests of concern are most likely to be transported to these Sydney estuaries. The results of this assessment can be used in various ways. They can help prioritise the marine pests to search for in each estuary, or identify vessels from particular countries that should be targeted for hull inspections for pests. For example, vessels entering Botany Bay that either originate from or have passed through Shanghai, Hong Kong or Auckland constitute the greatest general risk for introducing a species that might survive here and become a pest. It would also be prudent to develop eradication or containment plans for the pests identified as being likely to invade Sydney estuaries.

Given the relatively high likelihoods that the Asian bag mussel, *M. senhousia*, and the Asian clam, *P. amurensis*, could be introduced into Botany Bay, routine monitoring for these species would be advisable. Monitoring for *M. senhousia* could involve deploying settlement panels in Port Botany and retrieving them periodically, or doing visual surveys of the intertidal shoreline. The species is, however, most likely to colonise soft sediments which can rarely be sampled cheaply or cost effectively. Surveys for *P. amurensis* would be even more labour intensive as the species tends to live exclusively in subtidal soft sediments.

The following improvements to this vector-based assessment should be considered:

- Estimate the likelihood of secondary transport of pest species, for example, the potential spread of a new pest from Port Jackson to any other NSW estuary. This would essentially involve extending the assessment to the rest of NSW and so would have the added benefit of being able to identify which estuaries in NSW should be surveyed for which pests.
- Incorporate data on arrivals of international vessels whose first port of arrival in NSW is not Port Jackson or Botany Bay. If possible, all classes of naval vessels should also be included.
- Estimation of likelihoods of pests being transported by commercial ships could be made more accurate by incorporating information about the average time that particular vessels remain in port and the speed at which the vessels travel.
- Obtain better information on movements of recreational boats, using random phone surveys or other suitable techniques. It will be especially important to gather information on journeys by recreational boaters from Victoria to NSW because many of Australia’s major pests are present in Victorian estuaries and could be transported via boats.
- Refine oyster aquaculture vector risks by taking into account the specific farming techniques and stock movement methods used in each estuary.
- The online survey of recreational boaters provided some potentially useful data on antifouling practices, and this could be incorporated into future assessments to more accurately determine the risks that pests might be transported on the hulls of recreational boats. The survey also indicated that additional community education about marine pests would be worthwhile.

1. BACKGROUND

The effects of invasive species are often stated to be one of the greatest threats to native biodiversity, second in importance only to habitat destruction and modification (Gray 1997, Walker and Steffen 1997, Sala *et al.* 2000, Simberloff 2000). Invasive species are defined by the IUCN as "organisms (usually transported by humans) which successfully establish themselves, and then overcome, otherwise intact, pre-existing native ecosystems" (www.issg.org/). Here we consider pests a subset of invasive species and define them as species that become abundant and cause some sort of ecological and/or socio-economic impact (i.e., combining ecological and anthropocentric considerations, Rejmánek 1995).

Estimating the socio-economic impacts associated with invasive species is difficult, in part because they are so widespread, but it has been suggested that the total cost to society of terrestrial and marine invasive species in the USA is around US$137 million annually (Pimentel *et al.* 2000). In general, marine invasions have been less well studied than terrestrial invasions, but our relatively limited capacity to manage vectors for marine pests means that the potential exists for many more marine than terrestrial species to be introduced into Australia.

It has been suggested that the primary vector for the introduction of new marine species to Australia is commercial shipping, either in the ballast water, on the hull or inside sea chests (Allen 1953, Williams *et al.* 1988, Coutts *et al.* 2003). But the role of smaller recreational craft in transporting marine species over large distances, primarily by hull fouling, is becoming increasingly apparent (Johnson *et al.* 2001, Minchin *et al.* 2006). The aquarium trade is another important long range vector for some species, such as the invasive seaweed *Caulerpa taxifolia* (Creese *et al.* 2004). Domestic vectors include commercial and recreational boats, commercial fishing activities (boat and fishing gear), the aquaculture industry, natural dispersal via currents, and in specific cases, connections of waterways via canals (Ruiz *et al.* 1997). Once nonindigenous species have entered an estuary, their small-scale spread (and hence invasion) may be facilitated by artificial structures such as pilings, pontoons and seawalls (Glasby *et al.* 2007) which are becoming increasingly prevalent in urbanised estuaries (Carlton 1979, 1996; Ruiz *et al.* 1997, Cohen & Carlton 1998).

The global transport of propagules via ballast water has been estimated to be in the order of 10 000 species a day (Streftaris *et al.* 2005). Despite this enormous potential for pest incursions, it is relatively rare that a successful invasion occurs. Most propagules in ships' ballast water, for example, are likely to perish en route, or if they do manage to survive a journey, fail to establish viable populations at the arrival site (Elton 1958, Williamson & Fitter 1996, Mack *et al.* 2000). In contrast, seemingly established populations of an invasive species can suddenly crash (Simberloff & Gibbons 2004). Nevertheless, many marine invasions have occurred and have had detrimental impacts on natural ecosystems. Estuarine habitats, in particular, are under increasing threat from invasion (Cohen & Carlton 1998, Ruiz *et al.* 2000).

Concerns about the introduction of species such as toxic dinoflagellates, fishes, invertebrates and the seaweed *Undaria pinnatifida* in the late 1970s (e.g., Williams *et al.* 1978) led the Australian Quarantine and Inspection Service to introduce the 'Australian Ballast Water Management Guidelines' for international shipping in 1990. Soon afterwards, the UN-led International Maritime Organisation adopted similar guidelines, due largely to the concerns raised by Australia and Canada. A co-ordinated national approach to managing marine pests in Australia was hastened by the invasion and successful eradication of the black-striped mussel, *Mytilopsis sallei*, in Darwin in 1999 (Bax 1999, Willan *et al.* 2000). Two national working groups, composed of State and Commonwealth representatives, were then established in 2000, namely the National Introduced

Marine Pests Coordination Group (NIMPCG) and the Consultative Committee on Introduced Marine Pests (CCIMPE). The current national classification and management of marine pests in Australia is closely aligned with the management of ballast water and hull fouling on commercial vessels. Strategies include mandatory ballast water management requirements for international voyages to Australia, draft guidelines for managing biofouling on vessels entering Australian ports, interim arrangements for emergency responses to introduced marine pest incursions, and a national marine pest monitoring programme in selected commercial ports. A nationally-consistent approach to marine pest incursions in Australia is due to be in place by late 2008.

A list of marine pests of concern for Australia has been produced by CCIMPE, based largely on the work done by Hayes & Sliwa (2003) and Hayes *et al.* (2005). This so-called CCIMPE Trigger List consists of six species of holoplankton which are potential threats to human health (and not considered further here), 19 marine species that are still exotic to Australia, and 10 species that are established but not widespread in Australia (Table 5.1). An additional ten species that are considered less likely to have major impacts (and are generally widespread in parts of Australia) have been included on a Watching List and a further 13 species have been listed as requiring more information – these latter 23 species have not been considered here. In addition to the 29 trigger list species we have chosen to consider the New Zealand green lip mussel (*Perna canaliculus*) as a potential pest in NSW because it has previously been introduced to South Australia (where it was eradicated), and because it was recently found on the hull of a commercial ship that trades in Port Kembla (R. Willan, MAGNT, pers. comm.). It is also noteworthy that *P. canaliculus* have been found on Australian naval vessels (R. Willan, MAGNT, pers. comm.), but we were unable to include comprehensive data on movements of naval vessels in this assessment.

1.1. Environmental conditions

Clearly a pre-requisite for a species becoming a pest in a new region is that it is able to survive the environmental conditions of that region. So-called ‘environmental matching’ is a method used to identify the pests that are most likely to survive in a particular region (e.g., Alexandrov, 2003, Bomford & Glover 2004). Temperature and salinity are two important variables that can influence the survivorship and reproduction of marine species. It is also essential that the right habitats are available for a species to colonise. Environmental data can be used to (a) identify which known pest species are capable of surviving and reproducing in a target estuary and (b) identifying regions, or more specifically ports, throughout the world that have similar environmental characteristics to Sydney and therefore could be a source for potential pests (which have not yet been identified).

1.2. Commercial shipping

With more than 700 vessels entering Australia via Port Jackson and Botany Bay each year, the potential for the transport of marine pests is great. Recent analyses have confirmed the widely held belief that the best predictor for the number of invasive species in a country is the quantity of international trade (Westphal *et al.* 2008). Most commercial vessels do not have home ports per se, rather they operate on continuous trading links. Mandatory ballast water management requirements for international voyages to Australia were established in 2001. The Commonwealth requires that no international vessels discharge within 12 nautical miles of Australia’s coastline any ballast water that was taken up from ports or coastal waters outside of Australia’s territorial waters. Ballast water exchange must achieve 95% volumetric exchange or better and vessels must retain all ballast water records in vessel logbooks and make these available to Australian Quarantine and Inspection Service (AQIS) officers on request.

Hull fouling may be at present the most significant vector for marine pests given that it is not as tightly regulated as is ballast water exchange. In October 2005, AQIS introduced voluntary biofouling management requirements for commercial and recreational vessels less than 25 metres in length, or apprehended and abandoned vessels of any size. The guidelines are currently under review, with the aim of imposing mandatory biofouling requirements by late 2008. Biofouling management requirements will not be developed for vessels greater than 25 metres in length until there is international agreement (through the International Maritime Organisation) on how to proceed.

Many large commercial vessels have their hulls antifouled and cleaned regularly, but there are still various niche areas on a hull which do not get antifouled, or where antifouling paints are ineffective, and these can accumulate significant marine growth (Rainer 1995, Gollasch 2002, Coutts *et al.* 2003). There are also many invasive marine species that are relatively resistant to the compounds used in antifouling paints (Piola & Johnston 2006, Dafforn *et al.* 2008).

Port Jackson handles a wide range of vessels through its 15 berths, including dry bulk, bulk liquids, general cargo and motor vehicles. Facilities covering a total of 62 hectares are located in Darling Harbour and Glebe Island/White Bay. Private facilities are located at Gore Cove and Blackwattle Bay. Port Jackson is also a leading destination for cruise ships, with passenger vessel facilities located at Wharf 8 Darling Harbour and the Overseas Passenger Terminal at Circular Quay. Port Jackson is the only port in Australia with two dedicated cruise terminals.

The facilities in Port Botany consist of two container terminals with six container vessel berths and a bulk liquids berth, complemented by container support businesses, bulk liquid berth storage facilities and private berths at Kurnell. The existing container facilities are currently being expanded along with plans to expand bulk liquid handling facilities. These expansions will result in more than 80% of all shipping movements through Sydney Ports being concentrated in Port Botany (www.sydneyports.com.au/corporation/about_us/news_room/?a=3912).

1.3. Recreational boating

There are over 200 000 recreational boat owners in NSW (www.waterways.nsw.gov.au/recboat-profile_old.html). The majority of these vessels travel short distances and so could only transport pests within NSW. Despite the huge potential for aquatic pests to be transported by recreational craft, the role of these vessels as vectors has been acknowledged and investigated only recently (Johnson *et al.* 2001, Minchin *et al.* 2006). Different types of vessels can potentially spread marine pests in different ways. For example, trailer boats could transport species such as the seaweed *Caulerpa taxifolia* on their anchors or on the trailer itself (West *et al.* 2007). Moored vessels, which have their hulls almost permanently submerged, are prone to fouling and so could spread marine species that settle on hard surfaces, and they may also spread species via anchors. The type and age of antifouling paint on a vessel's hull can also significantly influence the risk of transporting marine pests (Floerl *et al.* 2005), with some antifouling paints preventing significant hull fouling for 9 – 18 months (Minchin *et al.* 2006). But, as for commercial vessels, there will be niche areas on the hulls of recreational vessels that are not well antifouled and so accumulate significant marine growth.

Some large recreational vessels travel overseas and enter NSW via one of the six mainland first ports of arrival, which include Port Jackson and Botany Bay. The Australian Customs Service records arrival information for these vessels, including details of previous ports each vessel has visited. Among recreational boaters, large superyacht vessels in excess of 60 m are the only vessels considered likely to pose a ballast water translocation risk, but few such vessels travel to NSW.

AQIS requires that all recreational vessels which are capable of carrying ballast water must exchange water beyond 12 nautical miles of Australia’s coast.

1.4. Aquaculture industry

Aquaculture has been implicated in the transport of various marine pests, often in the form of the species being farmed, but also associated species that travel incidentally with the cultured stock (Naylor *et al.* 2001; Minchin 2007, Mineur *et al.* 2007). The only significant aquaculture species in NSW is the Sydney rock oyster *Saccostrea glomerata*, which is farmed in 32 estuaries. The Pacific oyster (*Crassostrea gigas*) is farmed in Port Stephens and there are leases with triploid (functionally sterile) Pacific oysters in the Hawkesbury River, Georges River and the Shoalhaven/Crookhaven river system. Marine pests can potentially be transported throughout NSW via stock movements of these oysters, either on or in the oysters, or attached to infrastructure such as plastic trays. There is a variety of farming techniques currently used in NSW estuaries, including stick/tray and slats which can be deployed on intertidal racks, long line, dredge, and floating rafts or pontoons. Some of these methods potentially pose greater threats of marine pest translocation than others.

Stock is moved within and among estuaries to maximise optimal growing conditions. NSW DPI regulates stock movements to minimise the risk of spreading noxious species such as Pacific oysters and diseases such as QX. Marine pests, in particular fouling organisms, could be transported among estuaries on oyster sticks and trays, slats or rafts. Dredge farming involves depositing oyster shells on hard clean bottoms of estuaries for spat to settle on to, before harvesting the mature oysters by systematic dredging in 1 m wide strips. This latter technique is, however, uncommon and gear would almost certainly not be transported among estuaries.

1.5. Fishing

In general, recreational fishing is unlikely to be a significant vector for marine pests. Perhaps the most likely way pests could be transported by recreational fishers is via the collection of bait (i.e., using a pest as bait), or in nets or traps. Nets would be most likely to transport habitat-forming species growing on soft sediment, such seaweeds *Caulerpa* spp. or the screw shell *Maoricolpus roseus*. But in practice it is almost impossible to estimate the likelihood that a pest might be transported via recreational fishers. This is because we have very limited data on where recreational fishers go fishing and what techniques they use. Nor do we know the typical duration between fishing trips (which would affect the chances of marine species surviving in fishing gear). We considered trying to gather such information using an online survey of recreational boaters (described in Section 4.5.2), but it was decided that the chances of getting sufficient information would be slim and by trying we could compromise the recreational boating survey. Thus we have only considered commercial fishing as a vector in this assessment.

Eight commercial fisheries operate in NSW waters and both the vessels used in the fishery and the fishing gear should be considered potential vectors for marine pests. Importantly, there are currently no restrictions on the cleaning of gear in enclosed waters, so some pests can potentially be transferred from fishing grounds to sheltered waters where gear are typically cleaned.

Port Hacking has been closed to commercial fishing for 80 years. Botany Bay has been a recreational fishing haven for the past five years, meaning that no commercial fishing is permitted, and commercial fishing was banned in Port Jackson in February 2006. So for these Sydney estuaries, the only way marine species could be transported via the commercial fishing industry is on the hulls of vessels delivering their catch from nearby estuaries directly to Fish Receivers. The only registered fish receivers located on the water in the Sydney region are businesses associated with the Sydney Fish Market in Blackwattle Bay, and a Seafood Restaurant in Cockle Bay.

The Australian Fisheries Management Authority (AFMA) licence five Commonwealth fisheries which operate within waters off the coast of NSW, namely the Eastern Tuna and Billfish Fishery (ECT), Southern Bluefin Tuna Fishery (SBT), Gillnet Hook and Trap Fishery (GHT), High Seas Non Trawl Fishery (HSN) and the South East Trawl Fishery (SET). Catch disposal records show that up to 5 000 trips are made each year by Commonwealth fishing vessels to NSW ports from interstate ports via offshore fishing waters.

1.6. Natural currents

There is a variety of dispersal mechanisms utilized by different marine species. Many species release propagules into the water column where they are spread via currents. Some species have adults or vegetative fragments that might drift in the water column or 'raft' by attaching to floating objects (called secondary dispersal). Various marine organisms lack planktonic larval stages or any means for secondary dispersal, and so currents would be an insignificant vector for inter-estuarine transport. In general, fishes have the greatest dispersal range and macroalgae the smallest, while different species of invertebrates can disperse over a vast range of distances (Kinlan & Gaines 2003).

Amongst the marine invertebrates, there are species with feeding (planktotrophic) larvae that can remain drifting in the plankton for weeks to months, enabling long-distance dispersal (e.g., seastars, crabs and barnacles; Thornson 1950, Scheltema 1986). Some bryozoans, molluscs and corals have larvae that are nourished by yolk reserves (lecithotrophic larvae) and can therefore remain in the plankton for only hours to days, meaning dispersal is restricted a few kilometres at most (Graham & Sebens 1996). This is especially characteristic of species that brood their eggs and tend to produce a small number of large eggs. Various species of ascidians and bryozoans (common fouling organisms) whose non-feeding larvae settle very quickly would not travel much more than tens of metres from the adults (Keough & Chernoff 1987, Todd 1998). If eggs are released close to the seafloor, larvae may not travel up into the surface layers where currents tend to be greatest. Many of these invasive fouling organisms, however, attach to floating structures (Glasby *et al.* 2007), meaning eggs would be released near the water's surface, although obviously their buoyancy would dictate how far they could travel in surface currents.

Algae can be dispersed as spores or adult plants, and the latter have the potential to travel very long distances. For example, the invasive Japanese seaweed *Undaria pinnatifida* may spread many kilometres in currents (Forrest 2000) and so travel out of estuaries, colonise the open coast and then invade new estuaries (Russell *et al.* 2008). The primary vector for the invasive broccoli weed (*Codium fragile* ssp. *tomentosoides*) in the USA is believed to be currents, with plants potentially being spread up to 12 km (Carlton & Scanlon 1985). The invasive Asian brown seaweed *Sargassum muticum* has vegetative fragments that float and may spread some 40 km in oceanic currents (Shanks *et al.* 2003).

The invasive European green shore crab (*Carcinus maenas*) and northern Pacific seastar (*Asterias amurensis*) can have larval durations around 3 months, depending on water temperature (Byrne *et al.* 1997, de Rivera *et al.* 2007). Consequently, the larvae of green shore crabs have been estimated to disperse as far as 50 – 150 km (Shanks *et al.* 2003). Clams and mussels often have a secondary dispersal and settlement phase. That is, after a moderate larval period in the plankton, small post-larvae that have settled out of the plankton can disperse again via byssus-drifting. The byssus is a fibrous structure that attaches these animals to hard surfaces, but also acts to keep post-larvae buoyant, enabling them to disperse hundreds of kilometres in currents. Such long-range dispersal has been documented for the invasive American jacknife clam (*Ensis americanus*; Armonies 2001) and the brown mussel (*Perna perna*; Hicks & Tunnell 1995, but see Lasiak & Barnard 1995).

Natural dispersal of marine pests is clearly an important vector for many species, but it has rarely been considered empirically in risk assessments due to the complexities involved in quantifying connectivity via currents. Given Australia's geographical isolation and the relatively short planktonic duration of most marine pests, it is very unlikely that pests would be transported here via oceanic currents. Natural dispersal in oceanic waters is more likely to provide connections among estuaries over scales of tens of kilometres. This is perhaps more likely in NSW than in some other states because of the strength of the East Australia Current and its proximity to the coast (Roughan & Macdonald 2008).

2. NEED

Given that many marine pests can be transported in ships' ballast water, most management strategies around the world have focussed on exchanging ballast at sea and sampling ballast water for invasive organisms (Ruiz & Carlton 2003, plus see details of the Global Ballast Water Management Programme, GloBallast 2006). There are, however, numerous practical difficulties involved with regulating the transport of pests in ballast water. For example, it is not practical to remove all the ballast water (and hence propagules) from a vessel, nor is it simple to be sure which vessels have undertaken the mandatory exchange of ballast water. Various ways of overcoming these difficulties have been investigated, including the 'disinfection' of ballast water (e.g., filtration through 50 μm screen, Hillman *et al.* 2004) and genetic sampling of ballast water for invasive species. So called 'gene probes' have now been developed for three invasive species of concern in Australia: the toxic dinoflagellate Gymnodinium catenatum (Patil *et al.* 2005), the Pacific Oyster Crassostrea gigas, and the seastar Asterias amurensis (Deagle *et al.* 2003, Patil *et al.* 2004). Gene probes are apparently capable of distinguishing the target species from numerous similar species, and can detect as few as three oyster or seastar larvae per m^3 of ballast water (Patil *et al.* 2004). As such, they are potentially useful tools for assessing the risk associated with the transportation of ballast water. But, to date, gene probes have been developed for just a few marine pests and there is no laboratory facility set up in Australia to routinely analyse water samples for pest species.

No matter how much effort goes into protecting our borders from marine pests, some will slip through and become established. Vectors such as hull fouling (particularly on recreational vessels, fishing vessels, and commercial non-trading vessels), and the aquaculture and aquarium industries will always be difficult to regulate. Natural dispersal is of course impossible to control. There are several examples of time lags before populations of invasive species explode (Hengeveld 1989, Crooks & Soulé 1999, Simberloff & Gibbons 2004). So even if we could immediately prevent any new marine species arriving in Australia, it is possible that pests will still emerge from nonindigenous species introduced previously (Kowarik 1995, Low 2001).

A crucial factor in being able to control or eradicate any pest is early detection. This is one of the reasons a national monitoring program of selected commercial ports is again on the Australian Government's agenda. But given the large costs involved in monitoring for marine pests, and limited resources, it is essential that we have a better understanding of which pests are most likely to invade a port, such that sampling can be targeted to detect these species. Moreover, it would be naïve to assume that the next major marine pest in Australia will be one of the species on the CCIMPE target list. It is common that major pest incursions are not expected, so we must assume that any nonindigenous marine species (or indigenous one for that matter) could potentially become a pest in NSW. This study was designed to address these issues by identifying (i) which international ports have environmental conditions similar to Sydney ports, and so could potentially be the source of a marine species that could survive in Sydney estuaries and potentially become a pest, and (ii) which of the nationally-listed marine pests are most likely to survive in Sydney estuaries and be transported to them from international or domestic ports. The results of this study will therefore be useful for narrowing the focus of marine pest surveys in Sydney estuaries, by identifying the species most likely to arrive in each estuary, and the places within an estuary to which the larvae could be transported by currents.

3. OBJECTIVES

This project was designed to investigate the feasibility and applicability of using a vector-based approach for assessing the likelihood of marine pest introductions in NSW. As such, the project focussed on Sydney estuaries with the intention that, if successful, it could be extended to include all NSW estuaries. The specific objectives of this project were to:

1. Identify the international ports that are most likely to be the source of any marine species that could be introduced to Port Jackson or Botany Bay and become a pest (based on environmental similarity of the ports and amount of connectivity).
2. Identify which of the 29 nationally-listed marine pests, plus the New Zealand green lip mussel, *Perna canalicilus*, could survive and reproduce in Port Jackson, Botany Bay or Port Hacking (based on temperature and salinity tolerances only).
3. Of these species, identify which are the most likely to be introduced into Port Jackson or Botany Bay via international shipping and boating connections.
4. Determine the likelihood that any of the marine pests already in Australia could be transported to Port Jackson, Botany Bay or Port Hacking.

3.1. Scope

In some respects this study is not a true risk assessment because we have not considered the consequences of invasion for each marine pest, only the likelihood of each species arriving. Ecological risk is typically calculated as likelihood × consequence (Hayes 1997). But we have made the conservative, and arguably realistic, assumption that the invasion of any pest could have severe consequences and it is almost impossible to predict what those consequences might be. Furthermore, because we have based our assessment on a pre-defined list of potential marine pests (i.e., the CCIMPE trigger list), we consider that we are, by default, considering species that will have unacceptable consequences if they were to invade and establish. Thus, consequence is considered the same for each pest species, meaning that likelihood is directly proportional to risk. Hence we have used the terms likelihood and risk synonymously throughout this report. Importantly, our estimates of likelihood are not absolute, but rather are relative to each other. Thus, we cannot determine what the precise likelihood is for any invasion, but we can identify which species are more likely to invade than others.

The NSW estuaries examined for this project were Port Jackson, Botany Bay and Port Hacking. Only Port Jackson and Botany Bay are considered in terms of species arriving from overseas because Port Hacking is not a first port of arrival for international vessels. That is, a foreign-registered vessel arriving from overseas is not permitted to enter Port Hacking as their first Australian port, except in an emergency. The only vectors we have considered for international transport of marine species are commercial shipping (trading vessels and non-trading vessels such as barges, dredges, research vessels, etc.) and recreational boating (the latter is considerably less important in terms of numbers of vessels, but perhaps very important in terms of the potential for hull fouling). When considering these vectors we have assessed only the likelihood of transport among estuaries, not within. A potentially major international vector that we have not included, due to difficulties in obtaining accurate information, is the movement of naval vessels. The aquarium trade has also not been considered as a vector, despite potentially being important, because it is impractical to gather reliable data on where and when people might dispose of species from marine aquaria, thus making it impossible to estimate the likelihood of species being introduced via this vector.

We have not considered potential secondary transport of pests that are currently exotic to Australia. That is, we have not considered transport from Port Jackson, Botany Bay or Port Hacking to other NSW estuaries, but only potential transport to these estuaries from other NSW estuaries where pests are already present. Nor have we included information on the movement of international vessels whose first port of arrival in Australia was not Port Jackson or Botany Bay because such information was very difficult to compile. Thus, we have ignored any vessels that might have come to Port Jackson or Botany Bay from a high risk international port via another Australian Port.

The domestic vectors evaluated were commercial shipping (trading and non-trading vessels), recreational boating, commercial fishing (NSW and commonwealth fisheries), oyster aquaculture and natural transport via currents. Temporal variation in vector types or quantities has not been considered explicitly, although we have examined whether pests are likely to survive in Sydney estuaries in summer and winter.

In addition to calculating the likelihood of pests arriving in Sydney estuaries via currents, oceanographic models were used to determine where in Port Jackson and Botany Bay pests could be dispersed if they were released from a commercial vessel.

The 30 potential marine pests considered here include 29 species from the CCIMPE trigger list, plus the New Zealand green lip mussel (*Perna canaliculus*) because it has previously been introduced to South Australia and was recently found on a commercial vessel that trades in Port Kembla.

4. METHODS

4.1. Species biology and distributions

Literature from a range of sources was searched for data on temperature and salinity tolerances, optimal ranges, and distributions for each of the 30 species listed in Table 5.1. Scientific papers were searched using databases such as Current Contents and the Ocean Biogeographic Information System. In addition, web searches were done on species names and numerous invasive species databases were utilized, including The Nature Conservancy Database of Global Marine Invasive Species Threats (Molnar *et al.* 2008), the National Introduced Marine Pests Information System (Hewitt *et al.* 2002), the Global Invasive Species Database (www.issg.org/database), the National Exotic Marine and Estuarine Species Information System (Fofonoff *et al.* 2003) and the Global Biodiversity Information System (accessed through GBIF Data Portal, www.gbif.net). Molnar *et al.* (2008) was also used to provide some indication of the impact potential of the 30 pest species of concern (Table 5.1).

4.2. Environmental similarity of international ports with Sydney ports

Maximum and minimum sea surface salinity and temperature data were sourced for Sydney estuaries from a variety of field sampling studies, much of which was compiled by the NSW Department of Environment and Climate Change. Most field-based studies were done between 1982 and 2007, although some temperature data were also obtained from the 1960s and 1970s from oyster farmers. In addition, remotely-sensed sea surface temperature information was sourced from the New Zealand National Institute of Water and Atmospheric Research (NIWA) for 17 locations off the NSW coast. This information consisted of monthly temperature averages for 16 years (January 1992 to 2008) obtained from satellite data derived at 1 km resolution. These readings are considered accurate to within approximately 2 km of the coast of Australia.

The physical environments of major ports around the world were compared with physical environments in NSW to determine the likelihood that, should a species arrive, it would survive and reproduce here. Environmental information for more than 350 international ports was obtained from the Global Ballast Water Management Program (Globallast), run by the International Maritime Organisation (IMO) (Alexandrov, 2003). The database contains information on a variety of variables, but we chose to use only data on eight variables which were deemed to be the most relevant and reliable namely mean maximum and minimum water temperatures and salinities for summer and winter.

A multivariate analysis (using the PRIMER 6 program) was used to determine groupings of ports that had environmental parameters similar to Port Jackson and Botany Bay (which are essentially identical to each other). This process can be thought of as “environmental matching”. The data were normalised before calculating Euclidian distances between every combination of ports. Group average clustering was used to group ports and the resultant clusters were displayed using a dendrogram. A minimum similarity of 2 Euclidean distance units was used to determine which international ports clustered with the Sydney ports. Six ‘environmental similarity grades’ were defined, with a grade of six being applied to international ports most similar to Port Jackson and Botany Bay.

Clustering using temperature and salinity variables at the similarity level of 2 Euclidean distance units led to ports being grouped roughly according to broad latitudinal boundaries. For example, ports similar to Sydney were typically in the range of 12 – 38°S or 25 – 44°N. Ports that were positioned a long way up an estuary, however, typically had low minimum salinities and so did not group as would be expected based on latitude (i.e., temperature) alone. Some ports which had shipping connections with Port Jackson or Botany Bay were not included in the Globallast port environmental dataset, so we grouped them into the multivariate clusters according to their latitudes. Many of these additional ports were in New Zealand and we obtained water temperature data (no salinity data were available) from the National Institute of Water & Atmospheric Research which showed that their clustering based on latitude was appropriate.

4.3. Likelihood of transporting species by different vectors

For each of the 30 pest species of concern, a weighting was applied to each vector to indicate the likelihood that the species might be transported among estuaries via that vector (intra-estuarine transport was not the focus of this assessment). For example, the seaweed *Caulerpa taxifolia* grows primarily in soft sediments and does not reproduce sexually, so it is extremely unlikely to be transported in ballast water, or attached to the hull of a vessel, and is instead most likely to be transported on anchors of recreational vessels or in fishing nets. Conversely, the green shore crab *Carcinus maenas* has long-lived planktonic larvae and is known to settle and grow amongst oysters (the crab’s main food source). So *Carcinus* is far more likely to be transported with movements of oyster stock, or in ballast water, than it is by recreational vessels. Each species was given a weighting from 1 (extremely unlikely) to 5 (extremely likely) for each vector. Typically weightings ranged from 2 – 4 (being low, medium or high likelihood), but 5 was used in cases where there was documented evidence of a species being transported by that vector, or 1 was used if there was no known way that the species could be transported by a vector. Thus, we took a precautionary approach of never eliminating a vector based only on the likelihood that a species would not be associated with it (although vectors could be eliminated if they were not known to exist and therefore could not possibly connect ports, as described in Section 4.6 below).

4.4. International shipping

Data on some 1632 commercial and 77 recreational vessels (tourist yachts, superyachts, catamarans and other pleasure craft) arriving in Botany Bay or Port Jackson from 1/1/05 – 31/10/07 were obtained from the Australian Customs Service. Rather than determining simply the last port of call for each vessel, we obtained the names of up to 11 previous international ports of arrival for each vessel, with the average number being 5 previous ports. For the vast majority of commercial vessels this covered a travel time of 6 months or less (because the vessels visit Sydney ports frequently), but for two vessels this covered a 3 – 4 yr period. So, for example, if 563 connections were recorded between Hong Kong and Botany Bay, this does not mean that 563 vessels came directly to Botany Bay from Hong Kong, but that there were 563 records of a Hong Kong port in the recent voyage histories of vessels arriving in Botany Bay. This calculation of “total connectivity” of ports via commercial shipping is important because many potential marine pests could survive on parts of the hull of a vessel for long periods of time. In total, we used data on 8673 port connections for international vessels and 222 port connections for recreational craft.

We did not consider how long a vessel might have stayed in each port (which can influence the likelihood that pests might settle on the hull, or reproduce while in another foreign port), but rather we made the very conservative assumption that any time in a port could potentially result in colonisation of a marine pest on the hull, or uptake of larvae into ballast tanks, etc.

Shipping data were not sorted by season, but a preliminary analysis for the port with the most connections with Botany Bay (i.e., Hong Kong) showed no significant differences in number of vessels arriving between summer and winter.

4.5. Domestic vectors

4.5.1. Commercial shipping

The Sydney Ports Corporation provided data for vessels arriving in Port Jackson and Botany Bay over the period 1/11/2005 – 31/10/2007. Information included the arrival date, vessel type, previous and future domestic ports, and if relevant, previous international ports. The international port records were cross checked with records provided by the Australian Customs Service for overseas vessels and were found to match. International movements within the domestic shipping movement data set were omitted to avoid duplication of records.

A constraint of the assessment should be noted here, in that the domestic shipping records list only one previous port for vessels arriving to Sydney Harbour. The vessel voyage history of a vessel whose previous port was a “first port of arrival” before arriving to Sydney or Botany Bay would be of interest for a more comprehensive analysis of international shipping connections, but constraints on time and resources did not permit this further analysis.

4.5.2. Recreational boating

No data on the movements of recreational boaters in NSW are readily available, but recreational boating has the potential to be a very important vector for some marine pests. An anonymous online survey of recreational boaters was considered the most cost effective way to get some indication of people’s boating habitats. Australian Survey Research was commissioned to help prepare and distribute the survey. Recreational boaters were contacted via email using the contact lists of NSW Maritime, Boat Owners Association, Superyachts Australia and Yachting NSW. A limitation of this approach is that only people who had previously agreed to be on mailing lists could be contacted.

The survey questions covered a variety of topics (see Appendix 1 for full survey), but the information used in this report to address issues of connectivity was: type and size of boat, where the boat is primarily launched or moored, what other estuaries are visited and how frequently. For trailer boats, we specifically asked for details of movements among estuaries within a period of one week because it is unlikely that many pest species could survive out of water for any longer than this. For boats permanently in the water (e.g., moored vessels) we asked about movements among estuaries over the last 2 years because a marine pest could potentially survive on the hull for extensive periods of time.

Only people with larger vessels that were moored or berthed were asked questions about inter-state travel or international travel, because it was considered very unlikely that pests transported by trailer boats over such large distances would survive. We also attempted to run a similar online survey for recreational boat owners based in Queensland and Victoria to gather information about their trips to NSW waters, but there were too few responses to provide any meaningful results. Thus we do not have good data about movements of recreation boats from other states to Sydney estuaries.

4.5.3. Oyster aquaculture

Oyster producers are required to submit shipment movement log books each month, such that all stock movements could be tracked in the event of a disease outbreak. The data set is not up to date primarily due to a lag in the submission of log books, so the stock movement data used in our analyses related to the period 15/1/2001 to 09/5/2007 (and was extracted from the database on 24 September 2007).

The combined movements of oysters among estuaries over the entire 6.5 yr period were used to give the best estimate of connectivity via this vector. But any stock movements between estuaries that are no longer permitted (due to recent restrictions imposed by NSW DPI) were omitted from the analysis. We did not, however, distinguish between different farming techniques or stock movement methods, but rather considered the likelihood of transport of a particular pest to be the same for all methods.

4.5.4. Commercial fishing

Records of movements of NSW-licensed fishing vessels can be inferred only from monthly commercial catch records. There are, however, no commercial fishing activities currently permitted in Port Jackson, Botany Bay or Port Hacking, so no connectivity was considered among estuaries for this vector. However, the Australian Fisheries Management Authority (AFMA) compile catch disposal records for their Commonwealth-licensed fishing vessels, which may enter NSW estuaries to dispose of their catch, and potentially to clean their fishing gear. Cleaning of nets is an important potential vector for marine pests, but no data are available on where and when this is done.

We obtained from AFMA catch disposal records and logbook data for Commonwealth-licensed vessels over the period 1/7/2003 to 1/6/2007. Catch disposal records record the trip start and end date, the port of catch disposal and the receiver. Licensees are not required to record their port of origin, so vessel movements were tracked via individual vessel trip start and end dates, and ports of catch disposal. Catch and effort log book data provided information about the trip departure and return port, time, gear and method of fishing, and the resultant catch for each fishing operation. The port of catch disposal was used to identify connections with Port Jackson for the Commonwealth-licensed fisheries (the only registered fish receivers located on the water in the Sydney region are in Port Jackson). For NSW-licensed fishing vessels, however, it was too difficult to track vessel movements. NSW catch return records are recorded by Fishing Business number and a licensed fishing vessel. The introduction of the Share Management Fishery in February 2007 saw a change that allowed a fishing business to use a number of different vessels, but these vessels are not individually listed in catch return records.

4.5.5. Modelling oceanic and estuarine currents

The University of NSW (Dr Moninya Roughan) provided data on the likely connectivity of 19 NSW estuaries via oceanic currents. Full details are provided in Roughan and Hallam (2008) and summarized here. The Princeton Ocean model was configured for the NSW continental shelf, where the flow is dominated by the east Australia Current. The model spans 1025 km of the coast between 28.4°S and 37.5°S, and approximately 450 km offshore. Data on oceanic currents spanning 12 years (1992 – 2006) were incorporated into the hindcast model. The minimum depth considered by the model is 15 m. But due to an absence of oceanographic data from near shore regions of the state, the model does not explicitly address transport of water out of an estuary and onto the open coast in areas < 15 m depth. For this reason, the model cannot precisely describe connectivity among estuaries, but does provide a good indication of the potential relative connectivity of different near shore regions throughout the state.

Connectivity among the following estuaries or lakes was modelled: Clarence River, Coffs Harbour, Kalang River, Nambucca River, Southwest Rocks, Port Macquarie, Manning River, Wallis Lake, Port Stephens, Port Hunter, Lake Macquarie, Broken Bay, Port Jackson, Botany Bay, Port Hacking, Shoalhaven River, Jervis Bay, Clyde River and Twofold Bay. Particle tracking experiments were done by simulating releases of particles adjacent to the entrance of each estuary or lake. In each release area there were 9 different release points, with 30 particles being released at each point. The fate of particles was modelled for a maximum of 30 days, which corresponds to an above average larval duration for the marine pests under consideration here. A longer model run of 90 days (relevant for some species of crab) is currently underway.

4.6. Calculations of likelihoods of invasion

Technically, likelihoods are probabilities between 0 and 1 (Winer *et al.* 1991), so the values we have calculated here would more correctly be termed likelihood scores. The likelihood scores are, however, proportional to likelihoods and are indicative of the chances of particular events occurring. In this context, the likelihood of an international port being a source of any marine pest (not specially one of the 30 identified in Table 5.1) was calculated as:

Environmental similarity to Sydney ports × *Total number of shipping connections*

The likelihood that one of the 30 pests of concern might invade a Sydney port from overseas was calculated as:

Total number of connections × *species weighting for commercial shipping* × *presence of pest*

If a pest was not present in an international port, or no shipping connections were known to exist, then the likelihood of transport by commercial shipping was zero. The larger the final number, the more likely it was that a species might arrive in Sydney.

For calculations involving domestic vectors, it was necessary to have measures for each vector that were on a similar scale, otherwise calculations would be dominated by a vector that was measured over the largest scale. For example, numbers of commercial ships arriving in Botany Bay from Melbourne during the period 1/11/2005 – 31/10/2007 were in the order of 1000, whereas numbers of movements of oysters were not greater than 10. Even if a pest was given the highest weighting of 5 for association with oysters compared to commercial vessels, the contribution of oyster movement to any calculation of likelihood of transport would be negligible. Thus, all vector data were ranged to be between 0 and 5, with 0 indicating no known vector connections and 5 indicating the greatest connectivity. We first used the formula $y_i = \frac{y_i - y_{\min}}{y_{\max} - y_{\min}}$ (Legendre & Legendre, 1998) to range non-zero values between 0 and 1. Each value was then ranged between 1 and 5 by multiplying by 4 and adding 1.

The ranges of values were calculated using the maximum across the three Sydney estuaries, or in the case of currents, across all 15 estuaries for which connectivity had been modelled.

The likelihood that one of the 30 pests of concern might invade a Sydney port from another Australian port or estuary via a domestic vector was calculated for each vector as:

$$\textit{Ranged number of connections} \times \textit{species weighting for the vector} \times \textit{presence of pest}$$

and this product was then added for each vector to give a total estimate of likelihood per species.

Calculations of likelihood of invasion for each Sydney estuary were done without including information on what pests were currently present in that estuary. Consequently, some of the pests identified as being likely to invade a particular estuary might already be present in that estuary.

5. RESULTS

5.1. Species biology and distributions

After examining the available literature on tolerances and optimal ranges for temperature and salinity for each of the 30 pests of concern, we concluded that all species could potentially survive in Sydney estuaries (Table 5.1, Appendix 2). The round goby (*Neogobius melanostomus*) is, however, the least likely species to survive here as it typically lives in salinities from 1 – 20 psu. Although Sydney estuaries can experience salinities as low as 20 psu, this generally occurs in the upper reaches of estuaries, or in the surface waters (top 1 – 1.5 m) in the lower reaches of these estuaries after very heavy rainfall. In general, the salinity in the main parts of Port Jackson and Botany Bay where international vessels arrive would range from 30 – 36 psu, making it unlikely that the round goby would survive before being able to move into less saline waters upstream. As it happens, the round goby is also the least likely species to arrive here from overseas (Table 5.8).

Many of the 30 potential pests are likely to survive and reproduce in Sydney estuaries only at particular times of the year. For example, species such as *Eriochir sinensis*, *Crepidula fornicata*, *Perna canaliculus*, *Undaria pinnatifida* and *Varicorbula gibba* would probably not survive the warmer months in Sydney. But in such cases, it would be important to consider secondary spread to another estuary in NSW that has more suitable conditions year-round.

The habitats required by all 30 species are available in Sydney estuaries. Not surprisingly, the conditions necessary for reproduction and survival of juveniles were always within the tolerance range for adults. Thus, if sufficient adults or propagules of these species were to arrive in Sydney estuaries, there is a reasonable chance that they could establish a viable population.

The vast majority of marine pests of concern are found in South East Asia, where they are either native or introduced. Many of the 30 pests of concern are also found in New Zealand, Europe or the USA.

5.2. Environmental similarity of international ports with Sydney ports

The level of similarity chosen to group shipping ports was arbitrary, but conservative. As can been seen in Fig. 5.1, the group of ports containing the Sydney estuaries could easily be sub-divided into a further two groups (at ~1.5 Euclidean distance units), or more at lesser levels of similarity. Ultimately, at 0 Euclidean distance units, all ports are significantly different, but such discrimination would not be useful.

Using a similarity level of two Euclidean distance units, six groups of ports were distinguished. Ports which connected with the Sydney ports, but were not in the international Globallast data set, were then added to clusters depending on their latitudes. Those ports that have some shipping connection with Port Jackson or Botany Bay and were deemed to have similar environments based on a multivariate cluster analysis are listed in Table 5.2. These ports were given an environmental similarity grade of 6 in subsequent analyses to determine the riskiest ports (Section 5.6.1 below). Note that relatively few of the ports in the Globallast environmental dataset had connections with Sydney ports, hence there are far fewer ports listed in Table 5.2 than are depicted in Fig. 5.1.

Table 5.1. Likelihoods of various marine pests surviving in Sydney estuaries (H = high likelihood; L = low likelihood) based on temperature and salinity tolerances, and overall impact scores for each pest. Likelihood of reproduction (and juvenile survival) typically matches likelihood of adult survival in relation to temperature. * indicates limited data available. Note that likelihood of *Caulerpa racemosa* surviving has been determined based on data for *Caulerpa taxifolia*. Individual impact scores come from Molnar *et al.* (2008); no data available for *P. canaliculus*. To calculate overall impact, ecological impact and invasive potential were given a double weighting, before summing all four categories.

Introduced status [†]	**Scientific Name**	**Summer survival**	**Winter survival**	**Salinity tolerance**	**Ecological impact**	**Invasive potential**	**Geographic extent**	**Management difficulty**	**OVERALL IMPACT**
Exotic	*Potamocorbula amurensis*	L	H	H	4	4	4	4	24
	Eriocheir sinensis	L	H	H	4	4	4	4	24
	Sargassum muticum	H	H	H	4	4	4	4	24
	Siganus rivulatus	H	L*	H	4	4	4	4	24
	Mya arenaria	L	H	H	4	3	4	4	22
	Caulerpa racemosa	H*	H*	H*	3	4	4	4	22
	Perna perna	H	H	H	4	3	4	4	22
	Neogobius melanostomus	H	L	L	3	4	4	4	22
	Hemigrapsus takanoi/penicillatus	L	L	H	3	4	4	4	22
	Perna viridis [††]	H	L	H	3	4	4	3	21
	Hemigrapsus sanguineus	H	H	H	4	3	4	3	21
	Didemnum vexillum/lahillei	L	H	H	4	2	4	4	20
	Mnemiopsis leidyi	H	H	H	4	3	4	2	20
	Ensis directus/americanus	H	L*	H	3	3	4	4	20
	Crepidula fornicata	L	H	H	4	2	4	4	20
	Rapana venosa	H	H	H	4	1	4	4	18
	Marenzelleria wireni	H	H	H	3	1	4	4	16
	Charybdis japonica	L*	H	H	3	1	4	3	15
	Mytilopsis sallei	H	H	H	3	1	4	2	14
	Perna canaliculus	L	H	H	?	?	?	?	?
In NSW	*Caulerpa taxifolia*	H	H	H	4	3	4	4	22
	Carcinus maenas	H	H*	H	3	4	4	3	21
	Sabella spallanzanii	H*	H	H	3	3	4	4	20
	Codium fragile ssp. *tomentosoides*	H	H	H	4	2	4	4	20
	Maoricolpus roseus	L	H	H	2	3	3	4	17
In Australia	*Musculista senhousia*	H	H	H	4	2	4	4	20
	Undaria pinnatifida	L	H	H	3	3	4	4	20
	Varicorbula gibba	L	H	H	3	3	4	4	20
	Asterias amurensis	L	H	H	3	3	4	4	20
	Grateloupia turuturu	H*	H*	H	1	1	4	3	11

[†] *As at 30/06/08*

[††] *Possibly still present in Cairns*

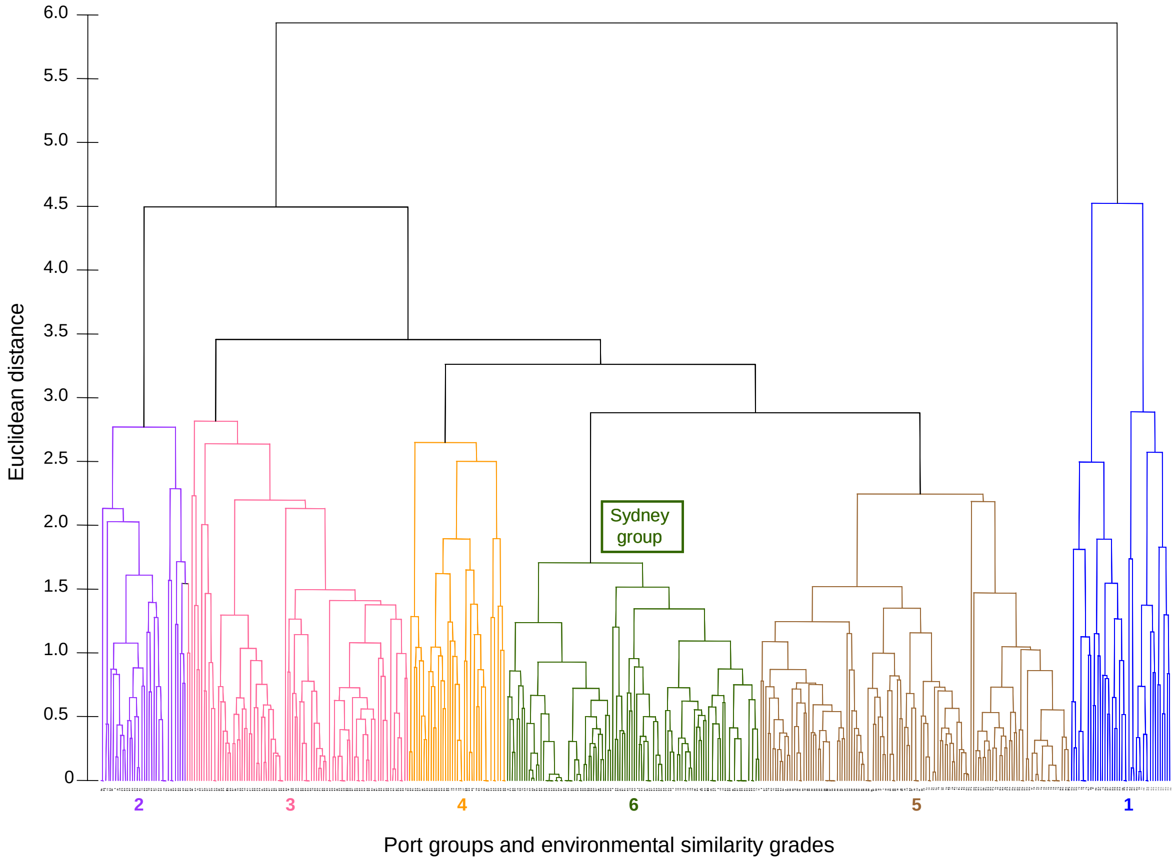

Figure 5.1. Dendrogram showing clustering of international ports and grades (on x-axis) based on a port's environmental similarity to Port Jackson and Botany Bay.

Table 5.2. Ports that are connected to Port Jackson or Botany Bay by commercial shipping and have similar environments (based on temperature and salinity data only). Ports in italics were added based on latitude as data on temperature and salinity were not available. Only those ports with high environmental similarity and large numbers of connections with Sydney ports were identified in subsequent analyses as likely origins for marine pests (see Table 5.8).

Arrival to Botany Bay		**Arrival to Port Jackson**	
Country	**Port of connection**	**Country**	**Port of connection**
Egypt	Port Said	*Chile*	*Valparaiso*
France	Fos sur Mer	Egypt	Port Said
France	Lavera	France	Fos sur Mer
Greece	Piraeus	*Italy*	*Barcellona*
Italy	*Gioia Tauro*	Italy	Genoa
Italy	Genoa	Italy	Livorno
Italy	Livorno	*Japan*	*Funabashi*
Japan	Kiire Kagoshima	Japan	Kiire Kagoshima
Japan	*Nagoya, Oita*	*Japan*	*Kanokawa*
Korea	*Jinhae (ex Chinhae)*	Japan	Kashima Ibaraki
Korea	Incheon	*Japan*	*Onahama*
Korea	Kwangyang	*Japan*	*Owase*
Korea	Pohang	*Japan*	*Sasebo*
Korea	Kunsan	*Korea*	*Incheon*
Korea	Onsan	Korea	Onsan
Korea	*Osan*	*Korea*	*Pyongtaek*
Korea	*Pyongtaek*	Korea	Pusan
Korea	Pusan	*Korea*	*Taesan*
Korea	*Taesan*	Korea	Ulsan
Korea	Ulsan	Korea	Yosu (Yeosu)
Korea	Yosu (Yeosu)	Malta	Malta (Valletta)
Mexico	*Ensenada*	*Mexico*	*Ensenada*
New Zealand	Auckland	New Zealand	Auckland
New Zealand	Marsden Point	New Zealand	Marsden Point
New Zealand	*Mount Maunganui*	*New Zealand*	*Opua*
New Zealand	*Manukau*	*New Zealand*	*Tauranga*
New Zealand	*Tauranga*	New Zealand	Whangerei
New Zealand	Whangerei	Spain	Barcelona
Peru	Callao (Lima)	Spain	Valencia
Portugal	Sines	USA	Los Angeles
Spain	Barcelona	*USA*	*Wilmington*
Spain	Las Palmas		
Spain	Valencia		
Turkey	*Dortyol Oil Terminal*		
Taiwan	Keelung (Chilung)		
USA	*Balboa*		
USA	Los Angeles		
USA	*Long Beach California*		
USA	*Newport News*		

5.3. Likelihood of transporting species by different vectors

There was good evidence available that some of the pests of concern had been introduced to new areas via particular anthropogenic vectors. For example, *Asterias amurensis* and *Hemigrapsus penicillatus* are known to have been introduced overseas via ballast water (Molnar *et al.* 2008), while *Codium fragile* ssp. *tomentosoides* and *Sargassum muticum* have been introduced via oyster aquaculture (Carlton & Scanlon 1985, www.issg.org/database). Various other species are known to have very long larval durations (e.g., 40 – 120 days), or adults that can be dispersed via currents (e.g., *Undaria pinnatifida*, Forrest 2000). All such species were given weightings of 5 for the corresponding vectors. Conversely, species with benthic eggs or that are extremely unlikely to be associated with particular vectors (because they would virtually never come into contact with the vector) were given weightings of 1. These weightings were used in the formulae described in Section 4.6 for calculating overall likelihoods of invasion. All weightings are listed in Table 5.3.

Table 5.3 Likelihoods that pests will be transported via different vectors which may connect Sydney estuaries with international or domestic ports. 1 = extremely unlikely, 5 = extremely likely.

Scientific Name	Commercial shipping	Commercial Fishing			Recreational Boating		Currents	Reference
		C'wealth Trawl	Other C'wealth	Oyster	Moored	Trailer vessel		
Potamocorbula amurensis	5	2	2	2	2	1	4	a, b
Eriocheir sinensis	2	3	3	3	3	1	4	
Sargassum muticum	3	3	3	5	3	4	4	c
Siganus rivulatus	3	1	1	2	1	1	5	
Mya arenaria	4	2	2	2	2	1	3	b
Caulerpa racemosa	1	1	1	3	1	4	2	
Perna perna	4	4	4	4	4	1	4	d
Neogobius melanostomus	4	3	3	3	3	1	2	b
Hemigrapsus takanoi/penicillatus	5	3	3	4	3	1	4	d
Perna viridis	4	4	4	4	4	1	3	
Hemigrapsus sanguineus	4	3	3	3	3	1	4	d
Didemnum vexillum/lahillei	4	5	5	5	5	1	1	b
Mnemiopsis leidyi	5	2	1	2	1	1	5	c
Ensis directus/americanus	4	2	2	2	2	1	5	d, e
Crepidula fornicata	4	4	4	5	4	2	4	f
Rapana venosa	3	3	3	5	3	1	1	g
Marenzelleria wireni	3	3	3	3	3	1	3	h
Charybdis japonica	3	3	3	4	3	1	5	i
Mytilopsis sallei	4	4	4	4	4	1	2	
Perna canaliculus	4	4	4	4	4	1	3	
Caulerpa taxifolia	1	1	1	3	1	4	2	
Carcinus maenas	4	3	3	5	3	1	5	d, j
Sabella spallanzanii	4	4	4	4	4	1	2	
Codium fragile ssp. *tomentosoides*	3	4	4	5	4	2	4	k
Maoricolpus roseus	3	5	1	1	1	1	3	l
Musculista senhousia	4	3	3	3	3	2	4	
Undaria pinnatifida	3	4	4	4	4	2	5	m, n
Varicorbula gibba	3	2	2	2	2	1	4	
Asterias amurensis	5	2	2	3	2	3	5	o
Grateloupia turuturu	4	3	3	3	3	2	3	

a = Parchaso & Thompson (2002), b = Molnar et al. (2008), c = Global Invasive Species Database (www.issg.org/database), d = Shanks et al. (2003), e = Armonies (2001), f = Lima & Pechenik (1985), g = Saglam & Duzguenes (2007), h = Burckhardt et al. (1997), i = Dineen et al (2001), j = de Rivera et al. (2007), k = Carlton & Scanlon (1985), l = Probst & Crawford (2008), m = Forrest (2000), n = Russell et al. (2008), o = Byrne et al. (1997).

5.4. International shipping connectivity

Over the period 1/11/2005 to 31/10/2007, 528 vessels arrived in Port Jackson from an international port, while 1181 vessels arrived in Botany Bay. Of these vessels, only 77 were recreational boats (56 being sailing vessels, the remainder motor boats) and all first arrived to Port Jackson.

Port Jackson handles a wide range of vessels via its 15 commercial berths, with the majority being passenger vessels, liquid product tankers, container vessels, or sailing vessels. Vessels arriving in Port Jackson have most connections with ports in New Zealand, New Caledonia, Singapore, Papua New Guinea, the United States of America, Japan, Vanuatu, Fiji, China and French Polynesia. If we were to consider only the immediate previous port of call for vessels arriving in Port Jackson (rather than total connectivity using the past 11 ports of call), then Auckland (New Zealand), Noumea (New Caledonia), Nelson (New Zealand), and Singapore would rank most highly.

Most international commercial vessels entering Port Botany are container vessels, with bulk liquid, liquid gas and chemical tankers making up the remainder. Vessels which arrive in Port Botany, predominantly have connections with ports in China, New Zealand, the United States of America, Hong Kong, Japan, Korea, Taiwan, France, Italy, Singapore, Belgium and the United Kingdom. If only the immediate previous port of call for vessels arriving in Botany Bay are considered, then Hong Kong, Auckland, Tauranga (New Zealand), Kaohsiung (Taiwan) and Ningbo (China) rank most highly.

5.5. Domestic connectivity

5.5.1. Commercial shipping

Both of the Sydney ports receive vessels from all over coastal Australia. Botany Bay receives almost twice as many commercial vessels as Port Jackson, but Port Jackson connects with more ports (34) than does Botany Bay (27).

The top ranking ports that connect with Botany Bay are Melbourne (1003 connections over the last 2 years), Brisbane (642), Fremantle (154), Westernport (49) and Port Jackson (35). Ranged rankings for all known domestic shipping connections with Botany Bay are presented in Table 5.4.

Port Jackson receives most of its commercial vessels from Brisbane (601), followed by Melbourne (335), Devonport (132), Port Kembla (91), Geelong (42) and Thevenard in South Australia (35). Ranged rankings for all known domestic shipping connections with Port Jackson are presented in Table 5.5.

5.5.2. Recreational boating survey

A total of 1650 responses to the online survey were received between 18 February 2008 and 7 March 2008. The responses were strongly biased towards Sydney-based boat owners, with 71% of all respondents having a home port in Broken Bay or Port Jackson. Forty-nine percent of those 1650 surveyed owned trailer boats, 44% owned boats stored via a mooring, berth or jetty, while the remaining 7% of those surveyed stored boats using a slipway, dry dock or boat shed. The majority of respondents (45%) owned boats 5 – 10m long, 32% of respondents owned boats 2 – 5 m long and 22% of respondents owned boats 10 – 20 m long.

Movements among estuaries were calculated for the following two categories: trailer boats that remain unused for less than a week during summer and winter, and vessels that are stored either by mooring, berth or by jetty. Results indicated that Port Stephens, Lake Macquarie, Pittwater, Hawkesbury, Port Jackson and Botany Bay are well linked by recreational boat traffic.

Specifically, Botany Bay was well connected with Port Hacking, Port Jackson and Broken Bay, particular via trailer boats (Table 5.4). Port Jackson was most connected to Broken Bay, Botany Bay and Lake Macquarie by moored boats and trailer boats, but it is also connected to many other smaller estuaries (Table 5.5). Port Hacking was most connected by trailer boats to Botany Bay, Port Jackson and Broken Bay (Table 5.6). The only estuary that is currently known to contain a marine pest not found in the Sydney region is Batemans Bay and this is connected to Port Hacking by trailer boats (Table 5.6). Batemans Bay was also connected to Botany Bay and Port Jackson via trailer boats (Tables 5.4 & 5.5). The pest in Batemans Bay (*Carcinus meanas*), could be transported via trailer boats, but would be far more likely to be transported by other vectors (Table 5.3).

During summer, trailer boat owners generally use their boats at least once per month (54% of respondents), yet 35% of respondents use their boats at least once per week, and 2% of respondents indicated they used their trailer boat daily. During winter, the majority of respondents use their trailer boat at least once per month (49%) or only about once per winter (34%).

The majority of respondents (16%) launch trailer boats in Broken Bay (Pittwater/Hawkesbury) or Port Jackson (15%), followed by Lake Macquarie (10%) and Port Botany (8%). Only 20% of trailer boat owners launched outside of NSW, the most popular destinations being Port Phillip Bay, the Gold Coast, Moreton Bay, and the Whitsundays. The majority of people who travelled interstate with their boats nominated Port Jackson or Broken Bay as their primary boating estuary.

Most of the vessels that were moored, berthed or on a jetty were based in Port Jackson (46%), or Broken Bay (Pittwater/Hawkesbury) (24%). The next most popular mooring location was Lake Macquarie (7%). Sixty four percent of those in this category used their boat at least once per week in summer, 54% used their boat at least once per month in winter.

Fifty eight percent of moored/berthed or jetty boaters visit other NSW estuaries or lakes outside of their usual home berth. It was common for boaters to stay up to a week at their boating destination (53%).

Sixteen percent of respondents with moored or berthed boats sailed outside of NSW waters. The most popular destinations were, in order, the Gold Coast (Southport), the Whitsundays (especially Hamilton Island), Hobart, the Sunshine Coast, Brisbane, and Mackay. Only 1.5% of these respondents travelled overseas and most went to Noumea or Auckland.

Information on antifouling practices was also obtained, but not used in this assessment. Boats permanently in the water were typically antifouled every 12 months (69%), every 18 months (17%) or every 6 months (6%). Only 2.1% of 422 respondents said they never antifoul their boats. Sixty eight percent of those people that antifoul the hull of their vessel use a biocidal antifouling paint and 14% use a non-toxic antifouling paint.

It was noteworthy that 23% of respondents indicated that, while boating, they would take up seawater, for example for toilet flushing or ballast, and later dump this in a different estuary or offshore.

5.5.3. *Oyster aquaculture*

There is, currently, no commercial oyster farming in Port Jackson or Port Hacking, so these estuaries should not be connected to any other in Australia via this vector (Tables 5.5 & 5.6). Oyster farming occurs in a few areas of Botany Bay, mainly in the Georges River and Woolooware Bay. Records indicate that oyster products are transported to Botany Bay from Camden Haven, Port Stephens, Hawkesbury River and Brisbane Water (Table 5.4). Only in Brisbane Water is there a known marine pest (*Caulerpa taxifolia*) and this species is also present in Botany Bay.

The total number of oyster stock movements in NSW varies considerably among years (e.g., 92 in 2001, 371 in 2002, 401 in 2004, and 276 in 2006). The reason for this variation in numbers of movements relates primarily to outbreaks of QX disease, meaning closures are imposed to restrict stock movements. The majority of oyster stock movements in NSW involve Hessian bags (34%) or plastic oyster trays (30%).

5.5.4. *Commercial fishing*

Port Jackson, Botany Bay and Port Hacking are all closed to commercial fishing. There are, however, registered fish receivers in Port Jackson, so commercial fishing vessels (either those with NSW licences or Commonwealth licences) do come into the port to unload their catch. Only large, moored vessels would unload catch in this way. If these vessels had previously been moored in a port that contained marine pests, it is possible they could transport these pests on their hulls. Pests could also be transported from other fishing grounds if fishing nets were cleaned within Port Jackson.

Commonwealth-licensed fishing vessels arrive in Port Jackson from 19 other estuaries or lakes. By far the most common port of origin for these vessels is Ulladulla (527 visits from all types of vessels over the last 4 years), followed by Port Kembla (290 visits), Port Stephens (173 visits) and Wallis Lake (87 visits). Inter-state connections include Mooloolaba (64 visits) and Southport (60 visits). The port with the greatest number of known pests that connects to Port Jackson via commercial fishing vessels is Twofold Bay (60 visits). All known connections between Port Jackson and other estuaries via commercial fishing are listed in Table 5.5.

5.5.5. *Connectivity of estuaries by currents*

The main feature defining the movement of particles along the coast of NSW is the south-flowing East Australia Current (EAC). Particles tended to remain adjacent to the coast between 33°S and 36°S, depending on the occurrence and position of the EAC separation, which varies over time. After 30 days, most particles had left the coastal area, but some had entered another estuary to the south (or more specifically, they were located adjacent to the entrance of an estuary).

The greatest connectivity between any two estuaries used in the model was between Lake Macquarie (source) and the Hunter River (sink), with 35% of released particles connecting these areas. The greatest connection involving a Sydney estuary was between Broken Bay (source) and Port Jackson (sink) (26% connectivity, Table 5.5). Particles from Lake Macquarie could also connect to Port Jackson (3.7%). Interestingly, there was also transport of particles northward from Port Hacking (8.5%) and Botany Bay (7.3%) to Port Jackson, but only in summer, not winter. The only other noteworthy connections with the other Sydney estuaries were between Botany Bay (source) and Port Hacking (sink) (8.3%) and between Broken Bay and Botany Bay (2.1%).

Table 5.4. Ranged values showing connectivity to Botany Bay for each domestic vector. Source-specific pests are those not known to occur in Botany Bay.

			Commercial Fishing			Recreational Boating			
Source estuary	**State**	**Domestic shipping**	**C'wealth Trawl**	**Other C'wealth**	**Oyster**	**Moored**	**Trailer vessel**	**Currents**	**Source specific pests**
Cairns	QLD	1	0	0	0	0	0	0	b
Townsville	QLD	1	0	0	0	0	0	0	
Mackay	QLD	1	0	0	0	0	0	0	c
Gladstone	QLD	1	0	0	0	0	0	0	
Brisbane	QLD	4	0	0	0	0	0	0	
Clarance River	NSW	0	0	0	0	0	0	1	
Port Macquarie	NSW	0	0	0	0	0	1	0	
Camden Haven	NSW	0	0	0	1	0	0	0	
Wallis Lake	NSW	0	0	0	0	0	2	0	
Port Stephens	NSW	0	0	0	1	1	2	0	
Newcastle	NSW	1	0	0	0	0	0	0	
Lake Macquarie	NSW	0	0	0	0	1	2	0	
Brisbane Water	NSW	0	0	0	1	1	0	0	
Hawkesbury	NSW	0	0	0	1	0	0	0	
Broken Bay	NSW	0	0	0	0	1	3	1	
Port Jackson	NSW	1	0	0	0	2	4	0	
Port Hacking	NSW	0	0	0	0	1	3	2	
Port Kembla	NSW	1	0	0	0	0	0	0	
Jervis Bay	NSW	0	0	0	0	1	2	0	
Batemans Bay	NSW	0	0	0	0	0	1	0	a
Twofold Bay	NSW	1	0	0	0	0	0	0	a,d,e
Melbourne	VIC	5	0	0	0	0	0	0	a,c,d,f,g,h
Geelong	VIC	1	0	0	0	0	0	0	a,c,d,f,g,h
Portland	VIC	1	0	0	0	0	0	0	g
Westernport	VIC	1	0	0	0	0	0	0	a,c,g
Burnie	TAS	1	0	0	0	0	0	0	
Bell Bay	TAS	1	0	0	0	0	0	0	c,g
Devonport	TAS	1	0	0	0	0	0	0	d,e
Risdon	TAS	1	0	0	0	0	0	0	a,c,e
Hobart	TAS	1	0	0	0	0	0	0	a,c,e,h
Port Bonython	SA	1	0	0	0	0	0	0	g
Port Adelaide	SA	1	0	0	0	0	0	0	a,d,g
Cossack Pioneer (oil terminal)	WA	1	0	0	0	0	0	0	
Dampier	WA	1	0	0	0	0	0	0	
Varanus Island	WA	1	0	0	0	0	0	0	
Barrow Island	WA	1	0	0	0	0	0	0	
Fremantle	WA	2	0	0	0	0	0	0	a,d,g
Kwinana	WA	1	0	0	0	0	0	0	
Darwin	NT	1	0	0	0	0	0	0	

a = Carcinus maenas, b = Perna viridis, c = Varicorbula gibba, d = Sabella spallanzanii, e = Maoricolpus roseus, f = Undaria pinnatifida, g = Musculista senhousia, h = Asterias amurensis, i = Grateloupia turuturu

Table 5.5. Ranged values showing connectivity to Port Jackson for each domestic vector. Source-specific pests are those not known to occur in Port Jackson.

			Commercial Fishing			**Recreational Boating**			
Source estuary	**State**	**Domestic shipping**	**C'wealth Trawl**	**Other C'wealth**	**Oyster**	**Moored**	**Trailer vessel**	**Currents**	**Source specific pests**
Port Douglas	QLD	0	0	0	0	1	0	0	
Cairns	QLD	1	0	0	0	1	0	0	b
Townsville	QLD	1	0	0	0	1	0	0	
Whitsundays	QLD	0	0	0	0	1	0	0	
Mackay	QLD	1	0	0	0	1	0	0	c
Keppel Bay	QLD	0	0	0	0	1	0	0	
Rosslyn Bay	QLD	0	0	0	0	1	0	0	
Port Alma	QLD	1	0	0	0	0	0	0	
Gladstone	QLD	1	0	0	0	1	0	0	
Bundaberg	QLD	1	0	0	0	1	0	0	
Hervey Bay	QLD	0	0	0	0	1	0	0	
Fraser Island	QLD	0	0	0	0	1	0	0	
Mooloolaba	QLD	0	0	2	0	1	0	0	
Brisbane	QLD	3	0	1	0	1	0	0	
Southport	QLD	0	0	2	0	0	0	0	
Gold Coast	QLD	0	0	0	0	1	0	0	
Ballina	NSW	0	0	0	0	1	0	0	
Evans Head	NSW	0	0	1	0	0	0	0	
Clarance River	NSW	0	0	0	0	1	0	1	
Coffs Harbour	NSW	1	0	2	0	1	0	0	
Port Macquarie	NSW	0	0	0	0	1	1	0	
Lord Howe Is	NSW	0	0	0	0	1	0	0	
Wallis Lake	NSW	0	0	2	0	0	1	1	
Port Stephens	NSW	0	0	3	0	2	2	1	
Newcastle	NSW	1	2	1	0	1	1	1	
Lake Macquarie	NSW	0	0	1	0	2	4	1	
Brisbane Water	NSW	0	1	1	0	1	2	0	
Broken Bay	NSW	0	0	0	0	5	5	4	
Botany Bay	NSW	1	0	0	0	2	4	2	
Port Hacking	NSW	0	0	0	0	2	2	2	
Port Kembla	NSW	1	5	1	0	1	2	0	
Lake Illawarra	NSW	0	0	0	0	1	2	0	
Jervis Bay	NSW	0	0	0	0	1	1	0	
Ulladulla	NSW	0	2	5	0	0	1	0	
Batemans Bay	NSW	0	0	0	0	1	2	0	a
Bermagui	NSW	0	0	2	0	0	0	0	a
Twofold Bay	NSW	1	0	2	0	1	1	0	a,d,e
Geelong	VIC	1	0	0	0	1	0	0	a,c,d,f,g,h
Melbourne	VIC	2	0	1	0	1	0	0	a,c,d,f,g,h
Bancroft Bay	VIC	0	0	0	0	1	0	0	
Paynesville	VIC	0	0	0	0	1	0	0	
Lake Wellington Marlay point Sale	VIC	0	0	0	0	1	0	0	
Portland	VIC	1	0	0	0	0	0	0	g
Cowes	VIC	0	0	0	0	1	0	0	a,g

a = Carcinus maenas, b = Perna viridis, c = Varicorbula gibba, d = Sabella spallanzanii, e = Maoricolpus roseus, f = Undaria pinnatifida, g = Musculista senhousia, h = Asterias amurensis, i = Grateloupia turuturu

(table continued on next page)

Table 5.5. (continued).

			Commercial Fishing			Recreational Boating			
Source estuary	**State**	**Domestic shipping**	**C'wealth Trawl**	**Other C'wealth**	**Oyster**	**Moored**	**Trailer vessel**	**Currents**	**Source specific pests**
Wynyard	TAS	0	0	1	0	0	0	0	
Burnie	TAS	1	0	0	0	0	0	0	
Bell Bay	TAS	1	0	0	0	0	0	0	c,g
Devonport	TAS	2	0	0	0	0	0	0	d,e
St Helens	TAS	0	0	0	0	1	0	0	a,f
Wineglass bay	TAS	0	0	0	0	1	0	0	a,f,i
Macquarie Hbr	TAS	0	0	0	0	1	0	0	c,e
Triabunna	TAS	0	0	0	0	1	0	0	a,f,i
Hobart	TAS	1	0	1	0	0	0	0	a,c,e,h
Port Huon	TAS	0	0	0	0	1	0	0	a,c,e,h
Port Arthur	TAS	1	0	0	0	0	0	0	a,c,i
Port Davey	TAS	0	0	0	0	1	0	0	c
Thevenard	SA	1	0	0	0	0	0	0	
Port Bonython	SA	1	0	0	0	0	0	0	g
Ardrossan	SA	1	0	0	0	0	0	0	a
Port Lincoln	SA	1	0	0	0	0	0	0	
Port Adelaide	SA	1	0	1	0	1	0	0	a,d,g
Cossack Pioneer (oil terminal)	WA	1	0	0	0	0	0	0	
Port Hedland	WA	0	0	0	0	1	0	0	
Dampier	WA	1	0	0	0	0	0	0	
Varanus Island	WA	1	0	0	0	0	0	0	
Fremantle	WA	1	0	1	0	0	0	0	a,d,g
Kwinana	WA	1	0	0	0	0	0	0	
Esperance	WA	1	0	0	0	0	0	0	d
Jabiru Venture (oil terminal)	NT	1	0	0	0	0	0	0	
Challis Venture (oil terminal)	NT	1	0	0	0	0	0	0	
Darwin	NT	1	0	0	0	1	0	0	

a = Carcinus maenas, b = Perna viridis, c = Varicorbula gibba, d = Sabella spallanzanii, e = Maoricolpus roseus, f = Undaria pinnatifida, g = Musculista senhousia, h = Asterias amurensis, i = Grateloupia turuturu

Table 5.6. Ranged values showing connectivity to Port Hacking for each domestic vector. Source-specific pests are those not known to occur in Port Hacking.

			Commercial Fishing			Recreational Boating			
Source estuary	**State**	**Domestic shipping**	**C'wealth Trawl**	**Other C'wealth**	**Oyster**	**Moored**	**Trailer vessel**	**Currents**	**Source specific pests**
Coffs Harbour	NSW	0	0	0	0	0	0	1	
Wallis Lake	NSW	0	0	0	0	0	1	0	
Port Stephens	NSW	0	0	0	0	1	0	0	
Lake Macquarie	NSW	0	0	0	0	1	0	1	
Brisbane Water	NSW	0	0	0	0	1	0	0	
Broken Bay	NSW	0	0	0	0	1	2	1	
Port Jackson	NSW	0	0	0	0	1	2	0	
Botany Bay	NSW	0	0	0	0	1	3	2	
Port Kembla	NSW	0	0	0	0	0	1	0	
Jervis Bay	NSW	0	0	0	0	1	1	0	
Batemans Bay	NSW	0	0	0	0	0	1	0	a

a = Carcinus maenas

5.6. Calculations of likelihoods of invasion

5.6.1. International ports most likely to be sources of unlisted pests

Environmental similarity and total volume of vector connectivity were used to assess which international ports were most likely to be sources of new marine pests, specifically species which have not yet been listed nationally on the pest trigger list. Botany Bay is far more likely to be at risk of invasion by marine pests than is Port Jackson (Table 5.7). This is primarily because Botany Bay has far more total connections with international ports, but also because Botany Bay tends to be connected to those ports that are similar environmentally. As can be seen in Figs 5.2 and 5.3, the two Sydney ports receive vessels from very different origins. To help with a relative comparison of risks of pests invading Botany Bay versus Port Jackson, we ranged the likelihood calculations to the nearest integer between 1 (least likely) and 5 (most likely). Botany Bay has connections with many ports in the highest risk and intermediate risk categories, with Shanghai, Hong Kong and Auckland being the most risky ports (Table 5.7, Fig. 5.2). Port Jackson, on the other hand, has connections with only six ports with a risk ranking of 2, and all other ports with which it is connected have risk rankings of 1 (Table 5.7, Fig. 5.3).

Table 5.7. Top 20 international ports that might be sources for any marine pest entering Botany Bay or Port Jackson. Rankings based on environmental similarity and total numbers of international shipping connections. Ranged risk from low (1) to high (5) helps compare relative importance of ports between Botany Bay and Port Jackson.

Arrival Port	**Rank**	**Country**	**Connecting port**	**Ranged Risk**
Botany Bay	1	China	Shanghai (Shihu)	5
	2	Hong Kong	Hong Kong	5
	3	New Zealand	Auckland	5
	4	Korea	Pusan	3
	5	Taiwan	Kaohsiung	3
	6	New Zealand	Tauranga	3
	7	New Zealand	Lyttelton	3
	8	Singapore	Singapore	2
	9	China	Ningbo (Beilun) Zhejiang	2
	10	China	Chiwan (Shenzhen) Guangdong	2
	11	USA	Los Angeles	2
	12	USA	Savannah Georgia	2
	13	New Zealand	Nelson	2
	14	New Zealand	Wellington	2
	15	Italy	La Spezia	2
	16	New Zealand	Port Chalmers	2
	17	China	Qinggdao (Longgang) Shandong	2
	18	China	Xiamen (Weitou) Fujian	2
	19	Colombia	Cartagena	2
	20	New Caledonia	Nouméa	2
Port Jackson	1	Singapore	Singapore	2
	2	Vanuatu	Port Vila	2
	3	New Zealand	Auckland	2
	4	New Caledonia	Nouméa	2
	5	New Zealand	Tauranga	2
	6	New Zealand	Napier	2
	7	New Zealand	Nelson	1
	8	Papua New Guinea	Port Moresby	1
	9	New Zealand	Opua	1
	10	New Caledonia	Ile des Pins	1
	11	Papua New Guinea	Lae	1
	12	Fiji	Suva	1
	13	Hong Kong	Hong Kong	1
	14	China	Shanghai (Shihu)	1
	15	French Polynesia	Papeete	1
	16	New Zealand	Wellington	1
	17	New Caledonia	Ouvea	1
	18	Vietnam	Vung Tau	1
	19	New Zealand	Lyttelton	1
	20	Fiji	Lautoka	1

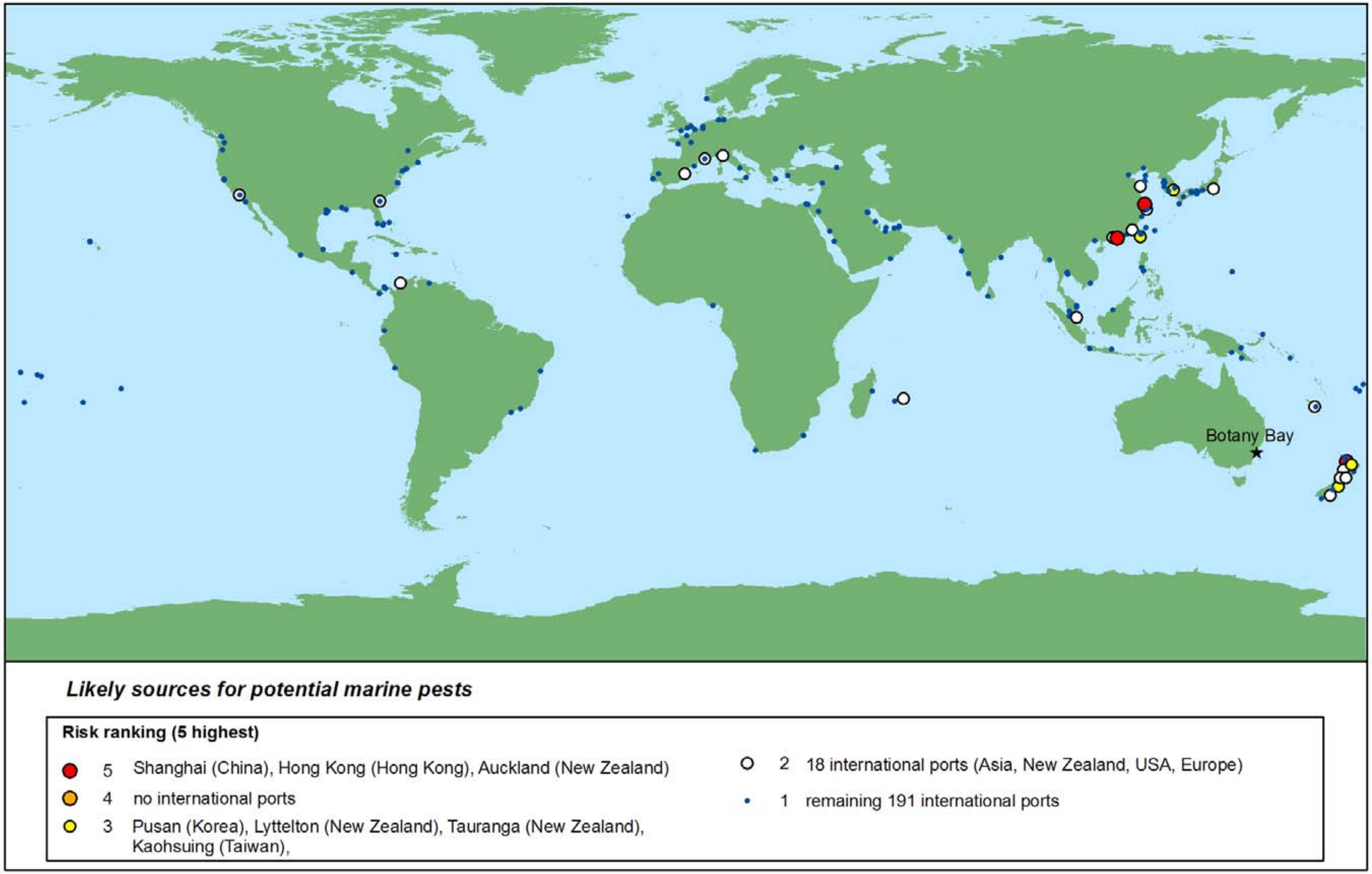

Figure 5.2. International ports that are most likely to be sources of new marine pests for Botany Bay (based on environmental similarity and total number of shipping connections).

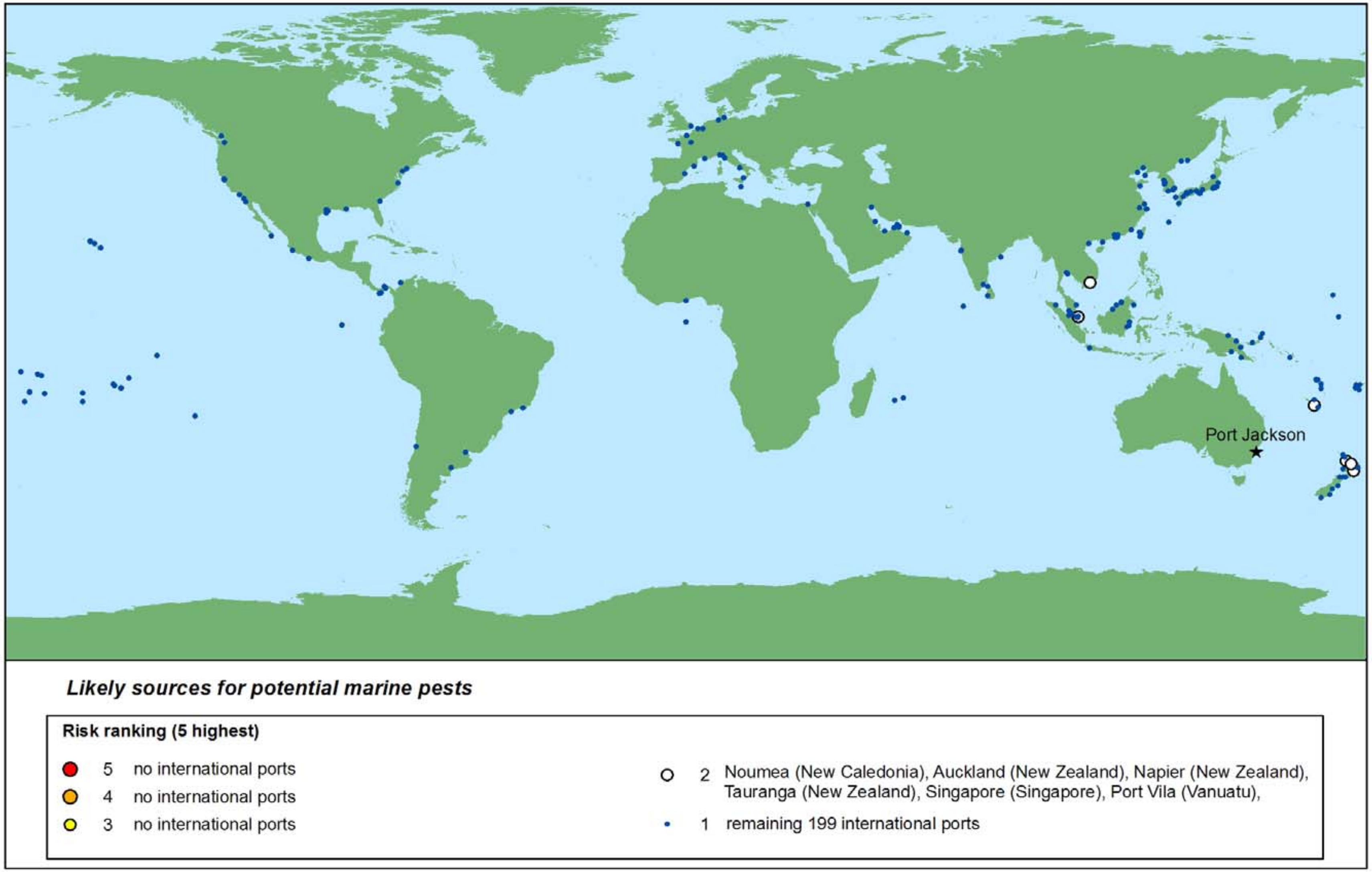

Figure 5.3. International ports that are likely to be sources of new marine pests for Port Jackson (based on environmental similarity of ports and total number of shipping connections).

5.6.2. Likelihoods of international invasions by recognised pests

Each of the 30 pest species of concern had some chance of being introduced into Botany Bay or Sydney Harbour based on international shipping or boating connections. The likelihoods for each species invading are not absolute, but rather are relative to each other. Thus, we cannot say what the precise likelihood is for any invasion, but we can say which species are more likely to invade than others. To help prioritise any future surveys for these pests, we have summed likelihoods across all ports of connection for each species, then ranged the resulting values to the nearest integer between 1 (least likely) and 5 (most likely). It is quite apparent that far fewer species are likely to invade Port Jackson than Botany Bay, and none of the pest species identified as a risk for Port Jackson rank higher than 2 (Table 5.8). This is in contrast to Botany Bay, which has rankings from 1 – 5, with the Asian bag mussel, *Musculista senhousia*, being the most likely species to invade. This result has occurred because Botany Bay has far more connections with ports that contain some of the 30 pests of concern.

Maps showing the riskiest ports for the highest ranked pests (ranged ranking 5 and 4) for Botany Bay are presented in Figs. 5.4 – 5.9.

Table 5.8. Relative risks for the 30 pests of concern invading Botany Bay or Port Jackson from international ports, summed across all ports of connection. Note that the top 13 pests listed for Botany Bay are all more likely to invade than is the first ranked pest for Port Jackson.

Rank	**Ranged risk**	**Botany Bay**	**Ranged risk**	**Port Jackson**
1	5	*Musculista senhousia*	2	*Perna viridis*
2	4	*Potamocorbula amurensis*	2	*Musculista senhousia*
3	4	*Undaria pinnatifida*	2	*Mytilopsis sallei*
4	4	*Hemigrapsus takanoi/penicillatus*	2	*Undaria pinnatifida*
5	4	*Perna viridis*	1	*Charybdis japonica*
6	4	*Hemigrapsus sanguineus*	1	*Codium fragile* ssp. *tomentosoides*
7	3	*Sargassum muticum*	1	*Didemnum vexillum*
8	3	*Mytilopsis sallei*	1	*Perna canaliculus*
9	3	*Charybdis japonica*	1	*Grateloupia turuturu*
10	3	*Rapana venosa*	1	*Sargassum muticum*
11	3	*Codium fragile* ssp. *tomentosoides*	1	*Potamocorbula amurensis*
12	3	*Asterias amurensis*	1	*Hemigrapsus takanoi/penicillatus*
13	3	*Mya arenaria*	1	*Caulerpa taxifolia*
14	2	*Didemnum vexillum*	1	*Maoricolpus roseus*
15	2	*Grateloupia turuturu*	1	*Hemigrapsus sanguineus*
16	2	*Carcinus maenas*	1	*Asterias amurensis*
17	2	*Eriocheir sinensis*	1	*Rapana venosa*
18	2	*Crepidula fornicata*	1	*Mya arenaria*
19	2	*Perna canaliculus*	1	*Caulerpa racemosa*
20	2	*Sabella spallanzanii*	1	*Sabella spallanzanii*
21	2	*Caulerpa taxifolia*	1	*Carcinus maenas*
22	2	*Maoricolpus roseus*	1	*Crepidula fornicata*
23	2	*Ensis directus/americanus*	1	*Eriocheir sinensis*
24	1	*Mnemiopsis leidyi*	1	*Varicorbula gibba*
25	1	*Varicorbula gibba*	1	*Siganus rivulatus*
26	1	*Siganus rivulatus*	1	*Ensis directus/americanus*
27	1	*Caulerpa racemosa*	1	*Perna perna*
28	1	*Marenzelleria wireni*	1	*Mnemiopsis leidyi*
29	1	*Perna perna*	1	*Marenzelleria wireni*
30	1	*Neogobius melanostomus*	1	*Neogobius melanostomus*

Figure 5.4. International ports that are the most likely sources for an invasion of Botany Bay by the Asian bag mussel *Musculista senhousia*.

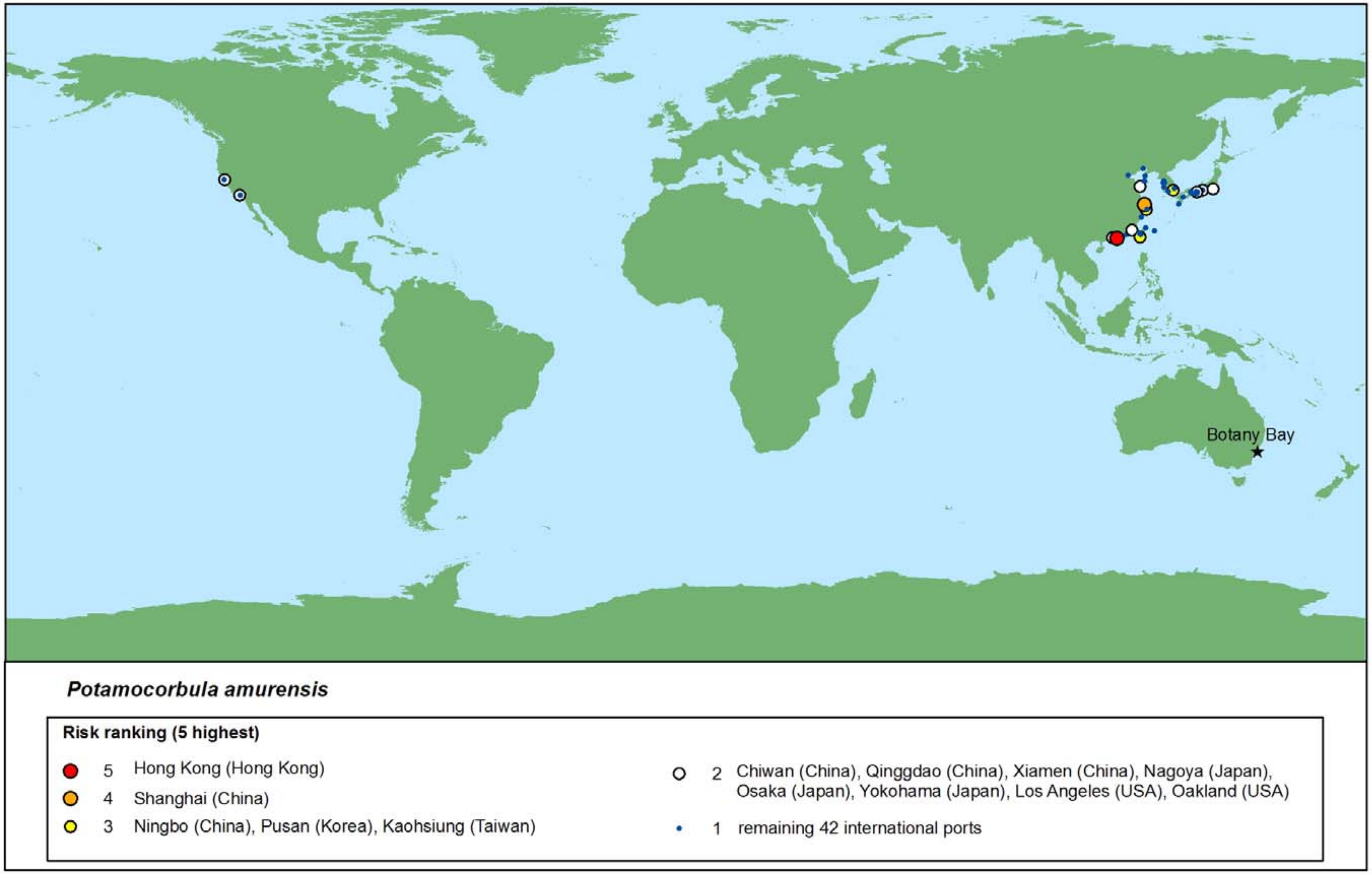

Figure 5.5. International ports that are the most likely sources for an invasion of Botany Bay by the Asian clam *Potamocorbula amurensis*.

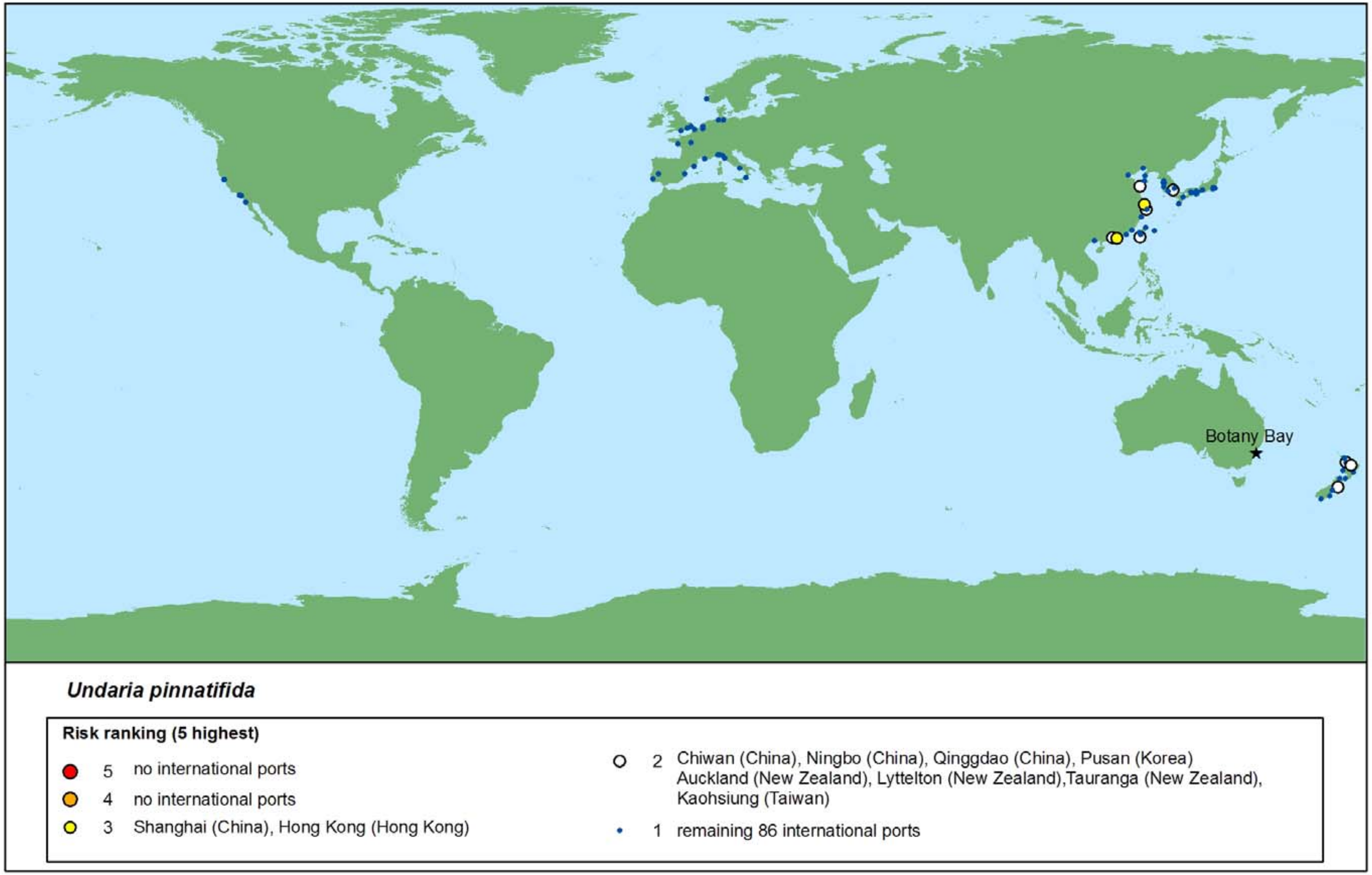

Figure 5.6. International ports that are the most likely sources for an invasion of Botany Bay by the Japanese brown seaweed *Undaria pinnatifida*.

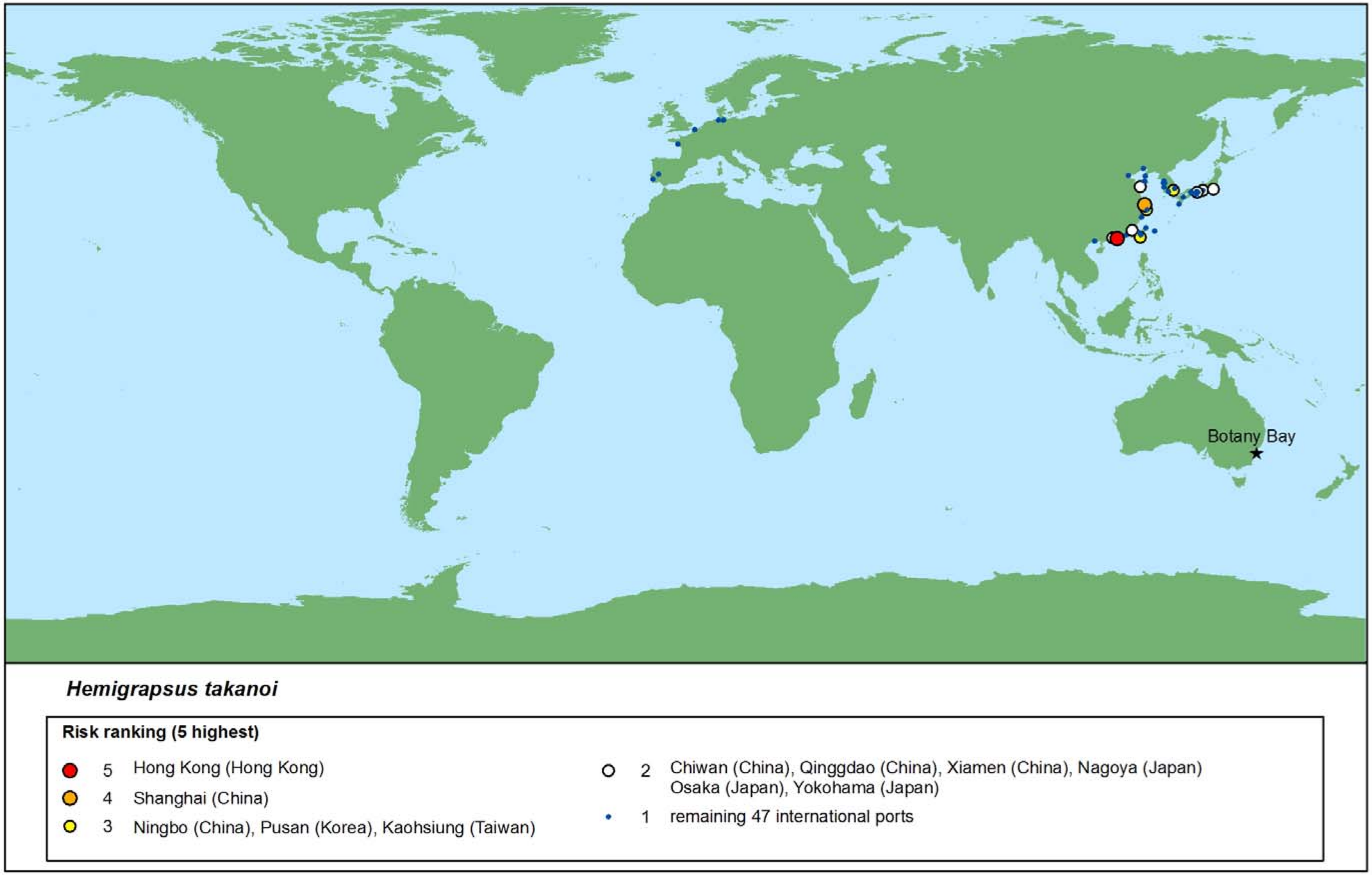

Figure 5.7. International ports that are the most likely sources for an invasion of Botany Bay by the Pacific crab *Hemigrapsus takanoi*.

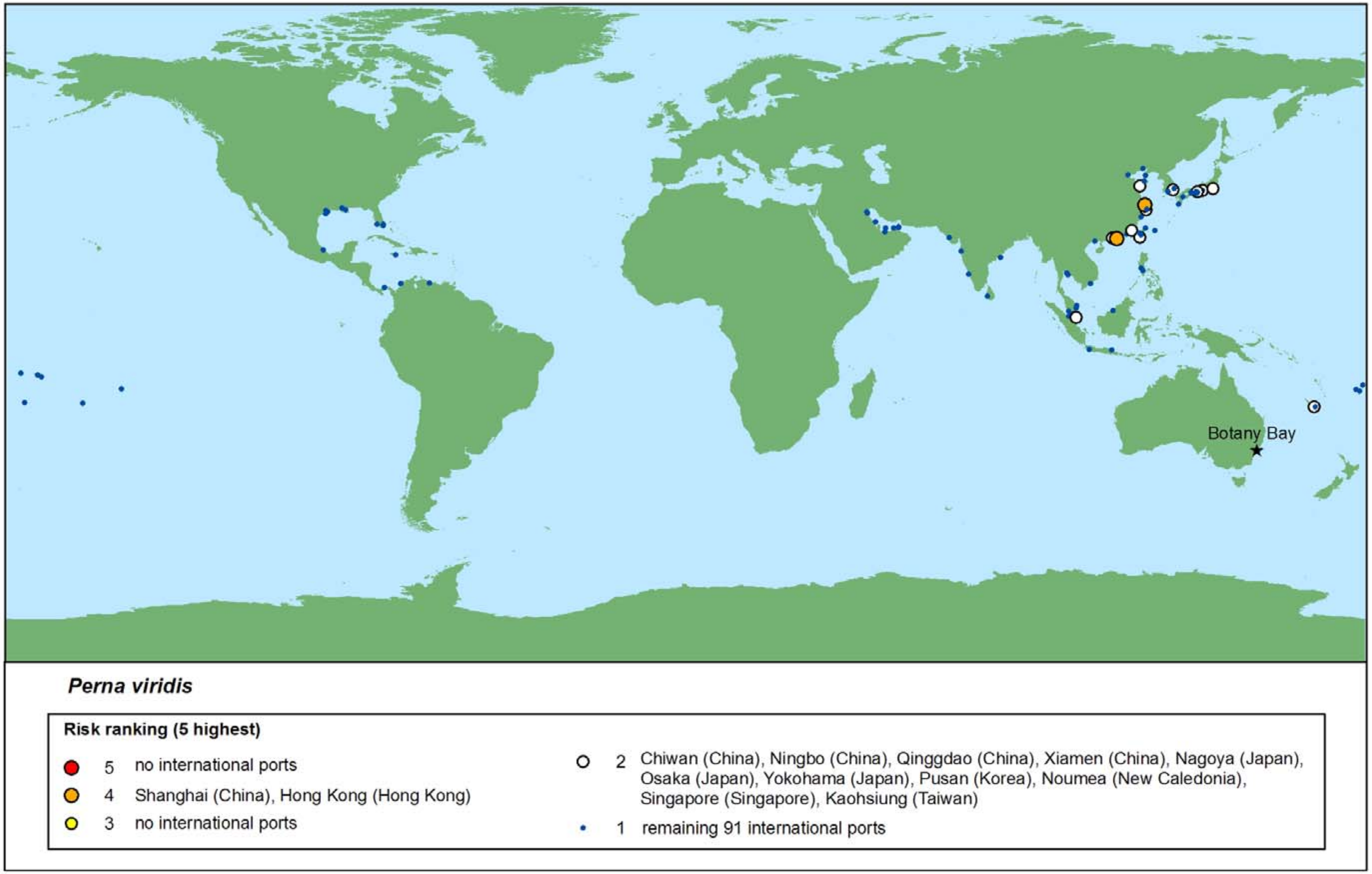

Figure 5.8. International ports that are the most likely sources for an invasion of Botany Bay by the Asian green mussel *Perna viridis*.

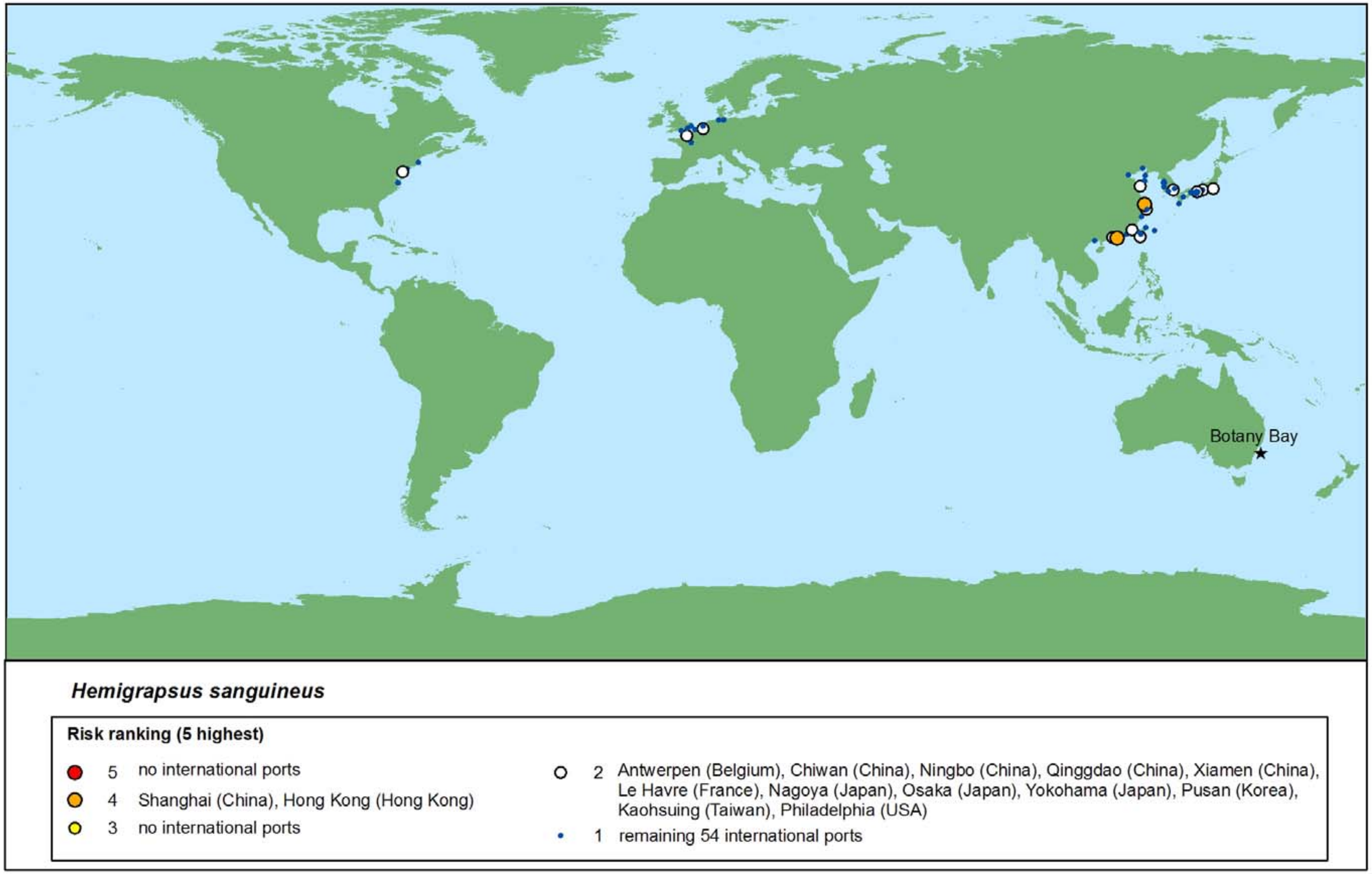

Figure 5.9. International ports that are the most likely sources for an invasion of Botany Bay by the Asian shore crab *Hemigrapsus sanguineus*.

5.6.3. Likelihoods of domestic invasions by recognised pests

We determined which Australian port was most likely to be the source of a marine pest for each of the Sydney estuaries by summing the likelihoods for all pest species, then ranging these values to the nearest integer between 1 and 5. The port of Melbourne was by far the most likely origin for a domestic marine pest invasion, ranking 5 for Botany Bay (Fig. 5.10) and 4 for Port Jackson (Fig. 5.11). The port of Melbourne has already been invaded by seven of the 30 pests included in our assessment, and only one of these (*Codium fragile* ssp. *tomentosoides*) is known to be present in Botany Bay and Port Jackson (plus there are historical records of the crab *Carcinus maenas* from these Sydney ports).

Port Jackson and Port Hacking were also likely to be sources of marine pests for Botany Bay (Fig. 5.10), but currently the same two pests are already found in each of these estuaries. The fact that pests that are already found in these estuaries were identified as being likely to invade indicates that our technique for assessing likelihoods of invasion is appropriate. Geelong, Fremantle, Hobart and Westernport were some of the other potentially important sources of new marine pests for Botany Bay (Fig. 5.10). Geelong was also a likely source of pests for Port Jackson (Fig. 5.11). Likelihoods for invasion of Port Hacking were all small compared to Botany Bay and Port Jackson, with no port having a ranged ranking greater than 2 and no inter-state ports being identified as potential sources of pests (Fig. 5.12).

Only 10 of the 30 pest species of concern had any chance of being introduced into Botany Bay via the vectors used in this assessment and the top two ranking species are already present in Botany Bay (Table 5.9). For Sydney Harbour, 11 of the pests could conceivably be introduced via these vectors (again, the top two have already invaded) (Table 5.9). Only three pests emerged as being likely to invade Port Hacking (of which *Caulerpa taxifolia* and *Codium fragile* ssp. *tomentosoides* are already present) and their associated risks were typically smaller than for the same pests in the other Sydney estuaries. Moreover, all the domestic ports that posed some risk for Port Hacking have the same two pests that are already present in Port Hacking, except Batemans Bay which also has *Carcinus maenas*. So in this regard, Batmeans Bay is at present the most likely source for a new pest for Port Hacking.

It is worth re-iterating here that the likelihoods of pests invading each target estuary were calculated without using data on the current status of pests in that target estuary. The high rankings for *Codium fragile* ssp. *tomentosoides* and *Caulerpa taxifolia* came about simply because each of the target estuaries in question is well linked to other estuaries that have these two pests. Specifically, Botany Bay is well connected with the port of Melbourne, Port Jackson, Port Stephens, Lake Macquarie and Port Hacking. Port Jackson is well connected with Broken Bay, Port Kembla, Botany Bay and Port Stephens.

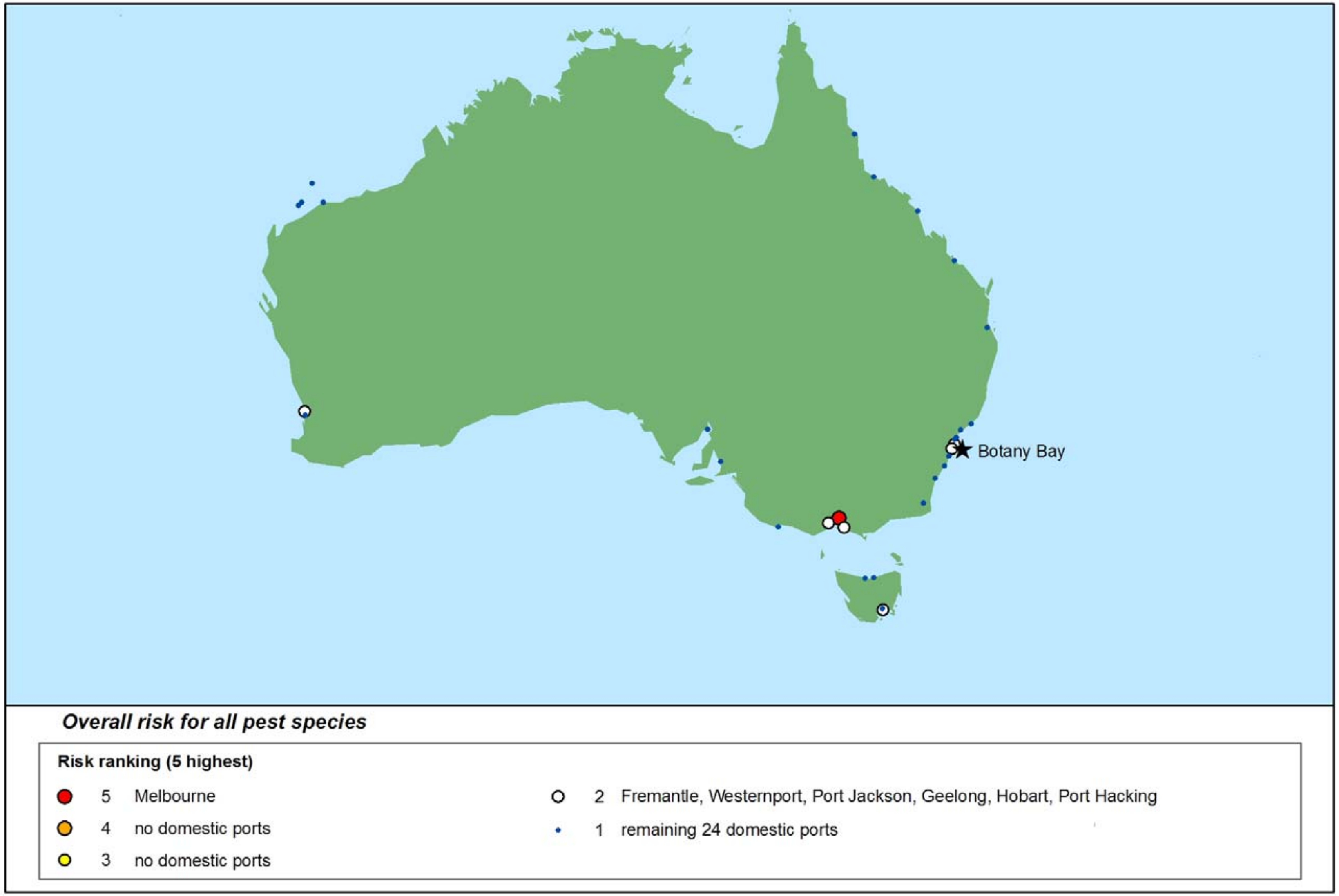

Figure 5.10 Domestic ports that pose the greatest risk to Botany Bay for a marine pest invasion.

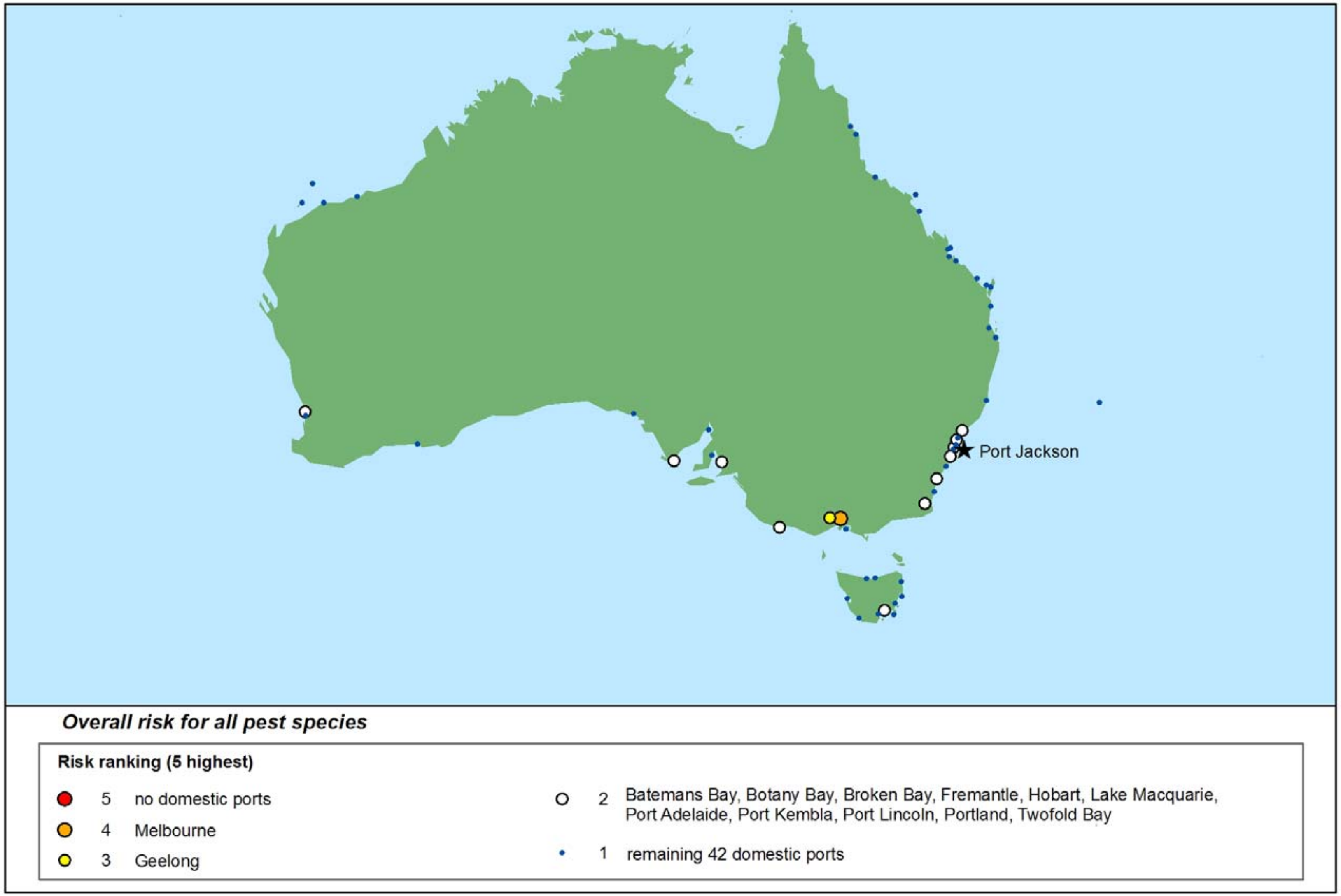

Figure 5.11. Domestic ports that pose the greatest risk to Port Jackson for a marine pest invasion.

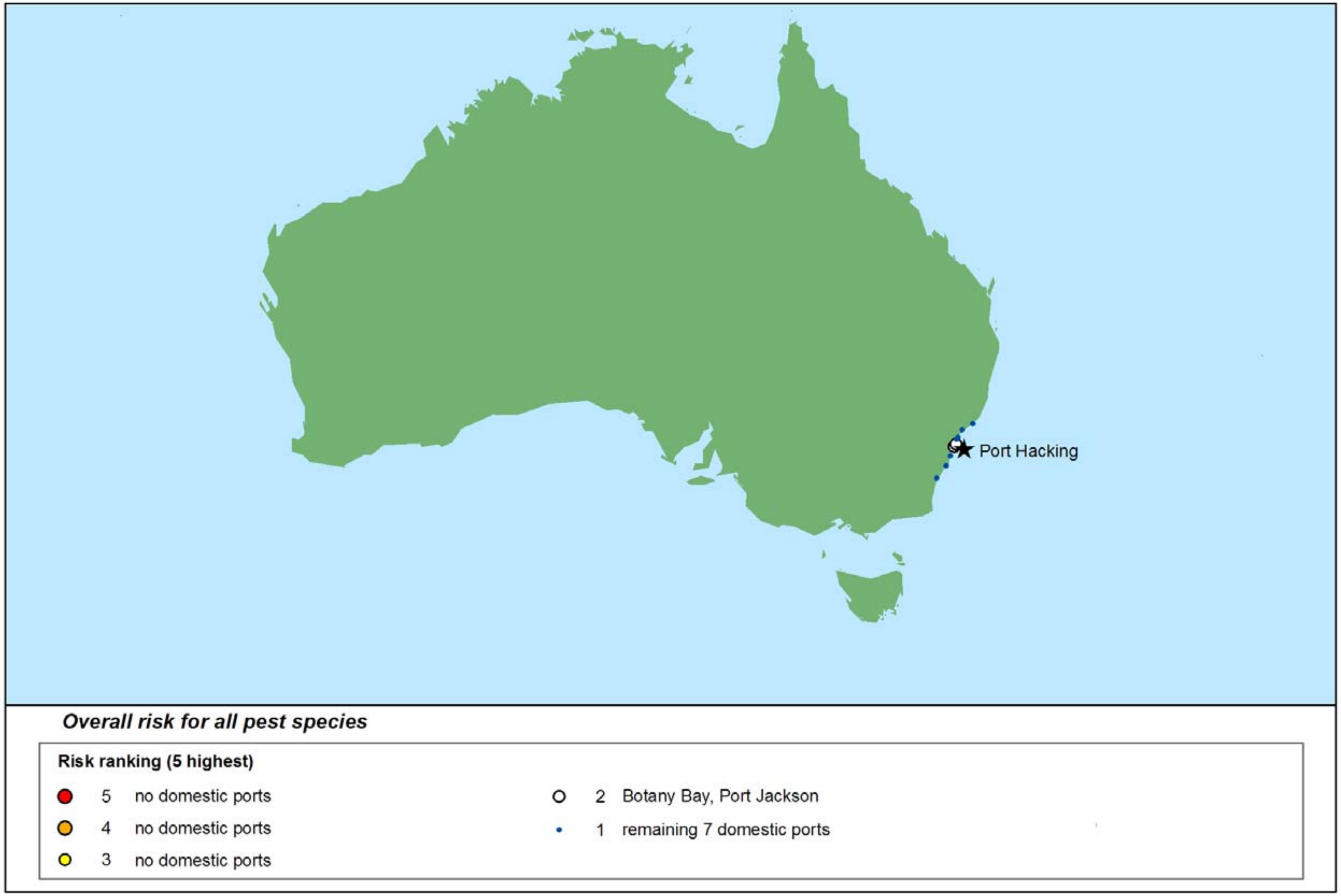

Figure 5.12. Domestic ports that pose the greatest risk to Port Hacking for a marine pest invasion.

Table 5.9. Relative risks of invasion by marine pests from domestic ports for Botany Bay, Port Jackson or Port Hacking. Only those pests with known vectors connecting them to any of these Sydney estuaries are listed.

Rank	**Botany Bay**		**Port Jackson**		**Port Jackson**	
	Ranged risk	Species	Ranged risk	Species	Ranged risk	Species
1	3	*Codium fragile* ssp. *tomentosoides*	5	*Codium fragile* ssp. *tomentosoides*	2	*Caulerpa taxifolia*
2	3	*Caulerpa taxifolia*	4	*Caulerpa taxifolia*	2	*Codium fragile* ssp. *tomentosoides*
3	2	*Carcinus maenas*	3	*Carcinus maenas*	1	*Carcinus maenas*
4	2	*Musculista senhousia*	3	*Sabella spallanzanii*		
5	2	*Sabella spallanzanii*	2	*Varicorbula gibba*		
6	2	*Asterias amurensis*	2	*Musculista senhousia*		
7	2	*Varicorbula gibba*	2	*Undaria pinnatifida*		
8	1	*Undaria pinnatifida*	2	*Asterias amurensis*		
9	1	*Maoricolpus roseus*	1	*Maoricolpus roseus*		
10	1	*Perna viridis*	1	*Grateloupia turuturu*		
11			1	*Perna viridis*		

6. DISCUSSION

Environmental matching of international ports and Sydney ports using temperature and salinity data identified 41 ports, from 14 countries, that had some connection with, and were similar to, Botany Bay (Table 5.2). Thirty four international ports, from 11 countries, have connections with, and are similar to, Port Jackson (Table 5.2). When total numbers of connections with each port are considered together with environmental similarity, Botany Bay is clearly more at risk of invasion than is Port Jackson, with the ports of Shanghai, Hong Kong and Auckland ranking as the most likely sources of a new pest for Botany Bay (Table 5.7). Environmental matching does not take into account the presence of any known pests, but rather assumes that if the environments are similar, there is a reasonable chance that a marine species living in the ports of Shanghai, Hong Kong or Auckland (either native to that port or introduced from another region) could also live in Botany Bay. The next most risky ports based on environmental similarity and numbers of connections with Botany Bay are Hong Kong, Auckland, Pusan (Korea), Kaohsiung (Taiwan), Tauranga (New Zealand) and Lyttelton (New Zealand). The most likely sources of a new pest for Port Jackson are Singapore, Auckland, Port Vila, Nouméa, Tauranga or Napier, but their likelihoods are less than for any of the aforementioned ports for Botany Bay.

Of the 30 marine pests of concern considered in this assessment, the Asian bag mussel *Musculista senhousia* was, based on number of vector connections, the most likely to arrive here from overseas. *M. senhousia* was considerably more likely to be transported from an international port to Botany Bay than to Port Jackson. The Asian bag mussel is not known to occur in NSW, but it has invaded estuaries in Victoria, South Australia, Tasmania and Western Australia. For this reason, *M. senhousia* also ranked highly as a pest that is likely to arrive in Botany Bay or Port Jackson from a domestic port. Although *M. senhousia* was not identified as a risk for Port Hacking (because there are no known connections between Port Hacking and another port that has *M. senhousia*), the connectivity we identified among Sydney estuaries means that any invasion of Botany Bay or Port Jackson could pose a significant secondary risk to Port Hacking. *M. senhousia* has a relatively high overall impact potential (Table 5.1) in part because it can smother benthic sediments, thereby excluding native invertebrates and potentially affecting the growth of seagrass beds, and foul structures (Willan 1987, Creese *et al.* 1997, Reusch & Williams 1998).

Of the next 11 most highly ranked pests that could arrive in Botany Bay from overseas ports, eight are not yet in Australia. Of these, the Asian clam, *Potamocorbula amurensis*, is the second most likely to arrive here after *M. senhousia,* and is also a greater risk for Botany Bay than for Port Jackson. *P. amurensis* is ranked as one of the most threatening marine pests in the world (Table 5.1) and could have significant impacts on sediments and native invertebrates, or alter natural fluctuations in phytoplankton abundance (Carlton *et al.*. 1990, Kimmerer *et al.* 1994, Murrell & Hollibaugh, 1998). The other marine pests not yet in Australia that ranked highly as potential invaders of Botany Bay included three crab species (*Hemigrapsus takanoi*, *Hemigrapsus sanguineus*, *Charybdis japonica*), the black-striped mussel *Mytilopsis sallei* (which invaded Darwin harbour in 1999 but was eradicated), the brown seaweed *Sargassum muticum*, and the whelk *Rapana venosa*.

Considering international and domestic connections in combination, the next most likely invaders are the northern Pacific seastar, *Asterias amurensis* (most likely to invade Botany Bay), the European green shore crab, *Carcinus maenas* (equally likely to invade Botany Bay or Port Jackson), and the Japanese kelp *Undaria pinnatifida* (more chance of invading Botany Bay, but also a high risk for Port Jackson). All of these species have already invaded Australia, and the green shore crab has been recorded recently from nine estuaries or lakes in southern NSW, the most northerly being Batemans Bay. Interestingly, there are historical records of the green shore crab for Port Jackson in the early 1900s and for Botany Bay as recently as 1987 (Ahyong 2005). Possibly the environment in these estuaries is not suitable to maintain a viable population of *C. maenas*, but surveys for the crab are being planned for the near future in an attempt to verify its present-day absence.

Based on the current known distribution of marine pests in Australia, the most important domestic vector that might result in a new pest incursion for Botany Bay is commercial shipping from Melbourne (Table 5.4). Recreational boating connections between all three Sydney estuaries and Batemans Bay could also be a risk for translocating the green crab *C. maenas* to Sydney. Most of these connections, however, involve trailer boats, which is the vector is the least likely to transport *C. maenas* (Table 5.3). Recreational boating also connects many estuaries in the greater Sydney region, particularly Lake Macquarie with Port Jackson, Botany Bay with Port Jackson, and Port Hacking with Botany Bay. It is notable that *C. taxifolia* has invaded all these estuaries and this seaweed can be spread via trailers and in anchor wells (West *et al.* 2007).

Many of the 30 potential pests are likely to survive and reproduce in Sydney estuaries only at particular times of the year. For example, species such as *Eriochir sinensis*, *Crepidula fornicata*, *Perna canaliculus*, *Undaria pinnatifida* and *Varicorbula gibba* would probably not survive the warmer months in Sydney. If these species arrived in winter and reproduced, then larvae or juveniles could potentially be transported to estuaries in the south of NSW where they would be far more likely to establish long-term populations. Future assessments should therefore consider secondary transport of species to other NSW estuaries.

This assessment identified as high risk a species that has previously been recorded in Port Jackson and Botany Bay (*C. maenas*), plus two other species that are already present in all three Sydney estuaries (*Codium fragile* ssp. *tomentosoides* and *Caulerpa taxifolia*), which indicates that the methodology used was appropriate. We re-iterate that the likelihoods of pests invading each target estuary were calculated without using data on the current status of pests in that target estuary. So the high domestic rankings for *C. meanas*, *C. fragile* ssp. *tomentosoides* and *C. taxifolia* came about because each of the Sydney estuaries is well linked to other estuaries that have these three pests. Specifically, Botany Bay is well connected with the port of Melbourne, Port Jackson, Port Stephens, Lake Macquarie and Port Hacking, which are all known to contain at least one of these three species. Port Jackson is well connected with Broken Bay, Port Kembla, Botany Bay and Port Stephens.

It should be noted that likelihoods of invasion (or more specifically of introduction) of pests that have been calculated here are relative only, not absolute. Thus, we cannot say what the precise likelihood is for any introduction, but we can say which species are more likely to invade than others, and which ports are the most likely sources of pests and by which vectors. Note also that a risk ranking of one does not necessarily mean a very small risk. For example, *C. taxifolia* had a domestic risk ranking of two for Port Jackson and for Port Hacking, and yet this species has already invaded each of these two Sydney estuaries.

Our estimates of likelihood of introduction of pests should be interpreted in terms of the information available about known vectors. This is particularly apparent for Port Hacking which would appear to have limited connections with any other NSW estuary. Obviously if other vectors were identified and quantified, the risks of pests being introduced could change greatly. Nevertheless, it seems unlikely that there are other significant vectors that should be included, other than the unquantifiable risk of pests being dumped from aquaria. It has been suggested, in fact, that the arrival of *Caulerpa taxifolia* in Port Hacking was the result of the seaweed being released from aquaria at the head of Gunnamatta Bay (Creese *et al.* 2004).

The reliability of the data we have used needs to be considered. Data on commercial shipping connections and aquaculture stock movements are apparently very reliable. Information about commercial fishing movements is relatively good, but we have not included connections of all NSW-licensed fishing vessels that unload their catch in Port Jackson. Also, we have probably slightly overestimated the connectivity of NSW commercial fishing vessels because some fishers reported their movements per fishing zone rather than per estuary (meaning that in these instances we had to assume the same level of connectivity among all estuaries within the zone), and also some fishers use multiple fishing boats, but data on the movements of individual vessels have not been recorded. Connectivity by oceanic currents has been estimated using a sophisticated oceanographic model, but limited data were available for nearshore currents along the NSW coast. For this reason, the results of the model cannot be assumed to be totally accurate, but they nonetheless provide the best possible estimate of connectivity among estuaries (M. Roughan, UNSW, pers. comm.). Information on recreational boating movements obtained from the web-based questionnaire is almost certainly biased and is probably the least reliable of any of the data on vectors. The bias of these data relates to the fact that the vast majority of respondents were based in Sydney, and only people who had previously agreed to receive emails from their boating organisation had the opportunity to participate in our survey. Given the response rate for this survey, the data on movements from Sydney estuaries to other estuaries in Australia is probably quite good. Data on intra-state movements to Sydney estuaries is, however, likely to be greatly underestimated and no data were obtained on inter-state movements to Sydney estuaries.

7. CONCLUSIONS AND FUTURE DIRECTIONS

This assessment has identified the international and domestic ports that are currently the most likely sources for marine pest incursions for Port Jackson, Botany Bay and Port Hacking. It has also identified which of the nationally-listed marine pests of concern are most likely to be introduced into these Sydney estuaries. Notably, different species are likely to be introduced into different estuaries due to different vector types and degrees of connectivity among estuaries. Although Port Hacking is unlikely to be the first point of invasion for pests from overseas, its considerable connectivity with Port Jackson and Botany Bay mean that it is at high risk of secondary invasion by new pests.

The results of this assessment can be used in various ways. They can help prioritise which marine pests to search for in each estuary, or identify vessels from particular countries that should be targeted for hull inspections for pests. For example, vessels entering Botany Bay that either originate from or have passed through Shanghai, Hong Kong or Auckland constitute the greatest general risk for introducing a species that might survive here and become a pest. It would also be prudent to develop eradication or containment plans for the pests identified as being likely to invade Sydney estuaries.

Given the relatively high likelihood that the Asian bag mussel, *Musculista senhousia*, and the Asian clam, *Potamocorbula amurensis*, could be introduced into Botany Bay, routine monitoring for these species would be advisable. Monitoring for *M. senhousia* could be a simple matter of deploying settlement panels in Port Botany and retrieving them periodically, or doing visual surveys for mussels along the intertidal shoreline. The species is, however, most likely to colonise soft sediments which can rarely be sampled cheaply or cost effectively. Surveys for *P. amurensis* would be even more labour intensive as the species tends to live exclusively in subtidal soft sediments. If the water clarity were adequate, video tows of the seafloor might be an option, but a grab sampler or benthic tow would be more appropriate and would generate large samples that would need to be sorted. Both *M. senhousia* and *P. amurensis* are small (no larger than 3 cm long), further adding to the difficulty of detection unless they have already become established and reached large densities.

The following improvements to this vector-based assessment should be considered:

- Estimate the likelihood of secondary transport of pest species, for example, potential spread of a new pest from Port Jackson to any other NSW estuary. This would essentially involve extending the assessment to all of NSW and so would have the added benefit of being able to identify which estuaries in NSW should be surveyed for which pests.
- Incorporate data on arrivals of international vessels whose first port of arrival in NSW is not Port Jackson or Botany Bay. If possible, all classes of naval vessels should also be included.
- Obtain better information on movements of recreational boats, using random phone surveys or other suitable techniques. It will be especially important to gather information on journeys by recreational boaters from Victoria to NSW because many of Australia’s major pests are present in Victorian estuaries and could be transported via boats. An opportunity to gather such information might arise in 2009 when a phone survey is being planned for NSW and Victorian recreational fishers (A. Steffe, pers. comm.).
- Estimation of likelihoods of pests being transported by commercial ships could be made more accurate by incorporating information about the average time that particular vessels remain in port and the speed at which the vessels travel.

- Refine oyster aquaculture vector risks by taking into account the specific farming techniques and stock movement methods used in each estuary.
- The online survey of recreational boaters provided some potentially useful data on antifouling practices, and this could be incorporated into future assessments to more accurately determine the risks that pests might be transported on the hulls of recreational boats. The survey also indicated that additional community education about marine pests would be worthwhile.

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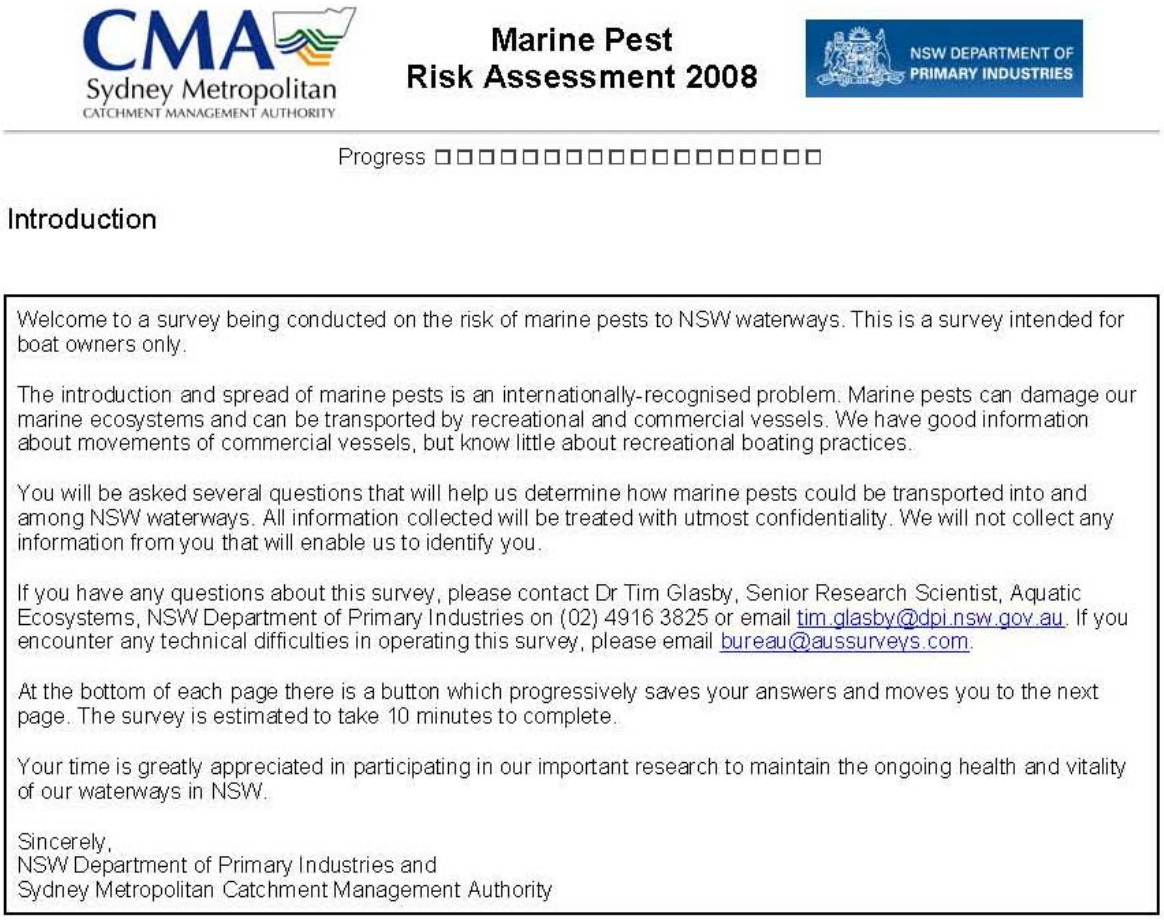
9. APPENDICES

Appendix 1. Screen grabs of online recreational boating survey. Note that the questions asked of participants in the latter sections of the survey depended on the answers they gave in earlier sections, so participants did not see every question.



**Marine Pest
Risk Assessment 2008**

Progress ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Introduction

Welcome to a survey being conducted on the risk of marine pests to NSW waterways. This is a survey intended for boat owners only.

The introduction and spread of marine pests is an internationally-recognised problem. Marine pests can damage our marine ecosystems and can be transported by recreational and commercial vessels. We have good information about movements of commercial vessels, but know little about recreational boating practices.

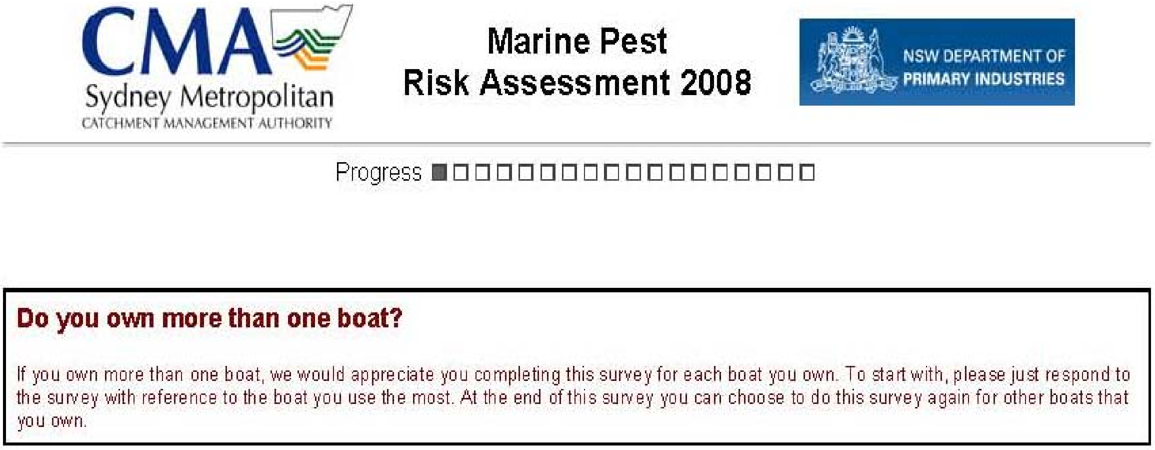
You will be asked several questions that will help us determine how marine pests could be transported into and among NSW waterways. All information collected will be treated with utmost confidentiality. We will not collect any information from you that will enable us to identify you.

If you have any questions about this survey, please contact Dr Tim Glasby, Senior Research Scientist, Aquatic Ecosystems, NSW Department of Primary Industries on (02) 4916 3825 or email tim.glasby@dpi.nsw.gov.au. If you encounter any technical difficulties in operating this survey, please email bureau@aussurveys.com.

At the bottom of each page there is a button which progressively saves your answers and moves you to the next page. The survey is estimated to take 10 minutes to complete.

Your time is greatly appreciated in participating in our important research to maintain the ongoing health and vitality of our waterways in NSW.

Sincerely,
NSW Department of Primary Industries and
Sydney Metropolitan Catchment Management Authority



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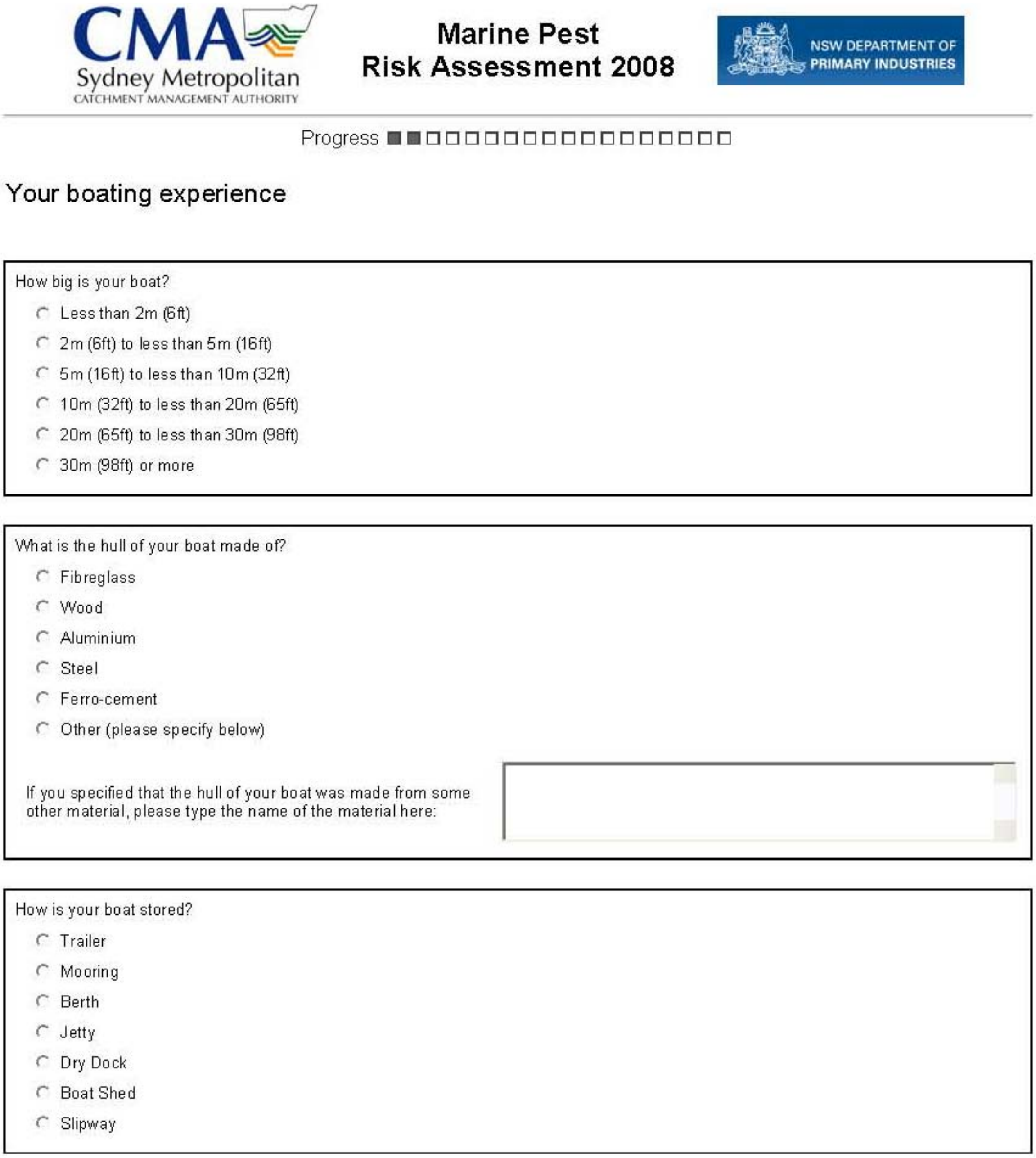
Do you own more than one boat?

If you own more than one boat, we would appreciate you completing this survey for each boat you own. To start with, please just respond to the survey with reference to the boat you use the most. At the end of this survey you can choose to do this survey again for other boats that you own.



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Your boating experience

How big is your boat?

○ Less than 2m (6ft)
○ 2m (6ft) to less than 5m (16ft)
○ 5m (16ft) to less than 10m (32ft)
○ 10m (32ft) to less than 20m (65ft)
○ 20m (65ft) to less than 30m (98ft)
○ 30m (98ft) or more

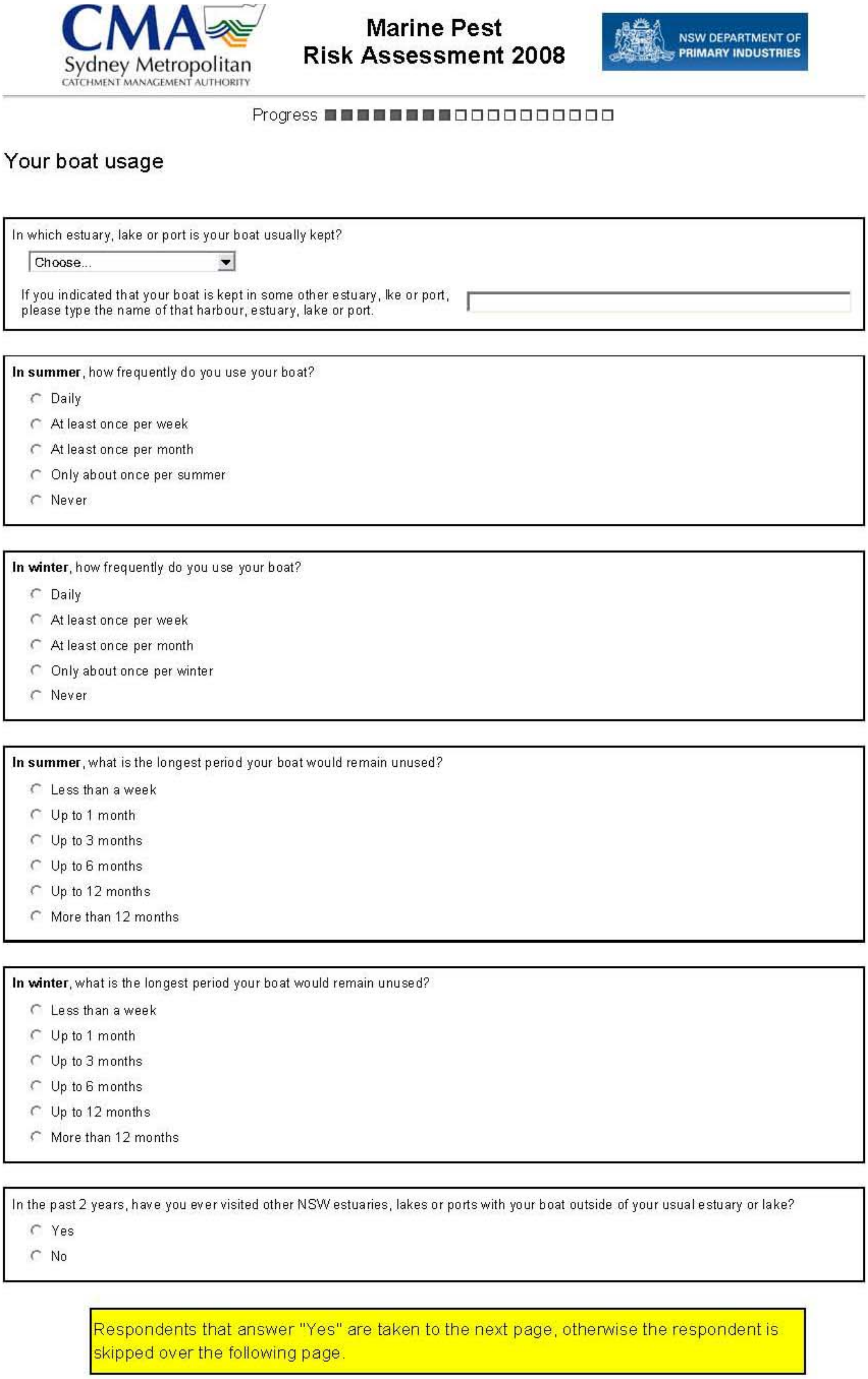
What is the hull of your boat made of?

○ Fibreglass
○ Wood
○ Aluminium
○ Steel
○ Ferro-cement
○ Other (please specify below)

If you specified that the hull of your boat was made from some other material, please type the name of the material here:

How is your boat stored?

○ Trailer
○ Mooring
○ Berth
○ Jetty
○ Dry Dock
○ Boat Shed
○ Slipway



CMA Sydney Metropolitan
CATCHMENT MANAGEMENT AUTHORITY

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NSW DEPARTMENT OF PRIMARY INDUSTRIES

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Your boat usage

In which estuary, lake or port is your boat usually kept?

Choose...

If you indicated that your boat is kept in some other estuary, lke or port, please type the name of that harbour, estuary, lake or port.

In summer, how frequently do you use your boat?

- ○ Daily
- ○ At least once per week
- ○ At least once per month
- ○ Only about once per summer
- ○ Never

In winter, how frequently do you use your boat?

- ○ Daily
- ○ At least once per week
- ○ At least once per month
- ○ Only about once per winter
- ○ Never

In summer, what is the longest period your boat would remain unused?

- ○ Less than a week
- ○ Up to 1 month
- ○ Up to 3 months
- ○ Up to 6 months
- ○ Up to 12 months
- ○ More than 12 months

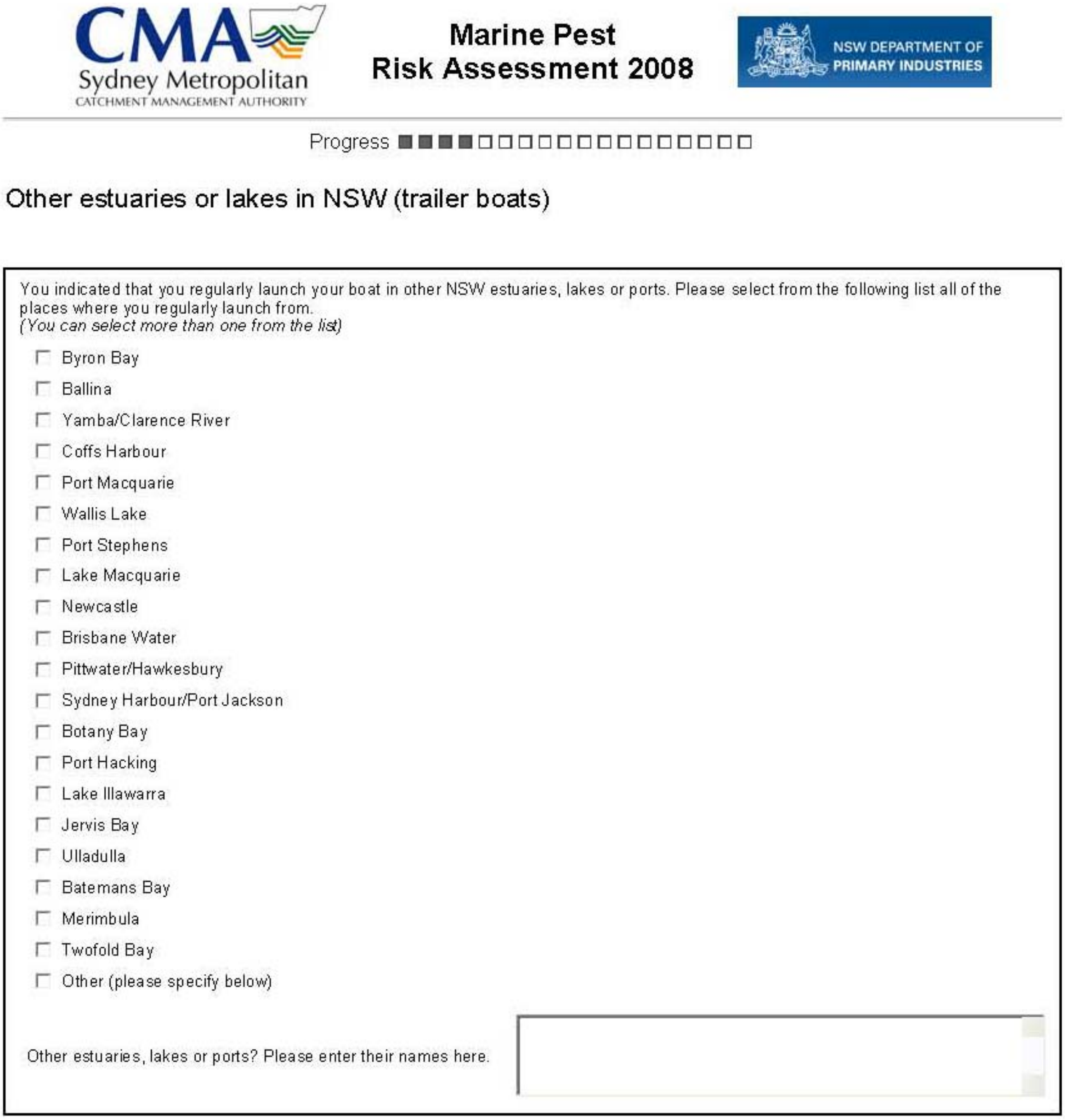
In winter, what is the longest period your boat would remain unused?

- ○ Less than a week
- ○ Up to 1 month
- ○ Up to 3 months
- ○ Up to 6 months
- ○ Up to 12 months
- ○ More than 12 months

In the past 2 years, have you ever visited other NSW estuaries, lakes or ports with your boat outside of your usual estuary or lake?

- ○ Yes
- ○ No

Respondents that answer "Yes" are taken to the next page, otherwise the respondent is skipped over the following page.

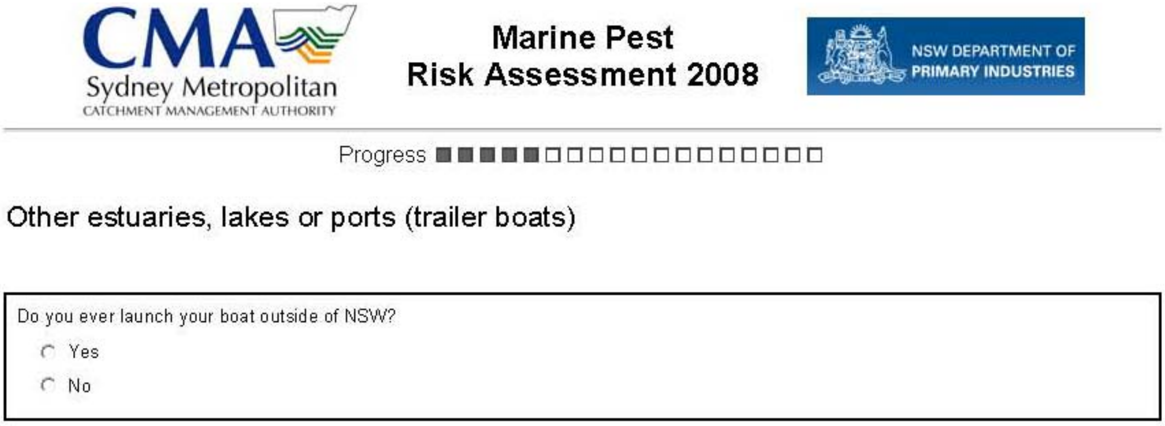


Other estuaries or lakes in NSW (trailer boats)

You indicated that you regularly launch your boat in other NSW estuaries, lakes or ports. Please select from the following list all of the places where you regularly launch from.
(You can select more than one from the list)

- ☐ Byron Bay
- ☐ Ballina
- ☐ Yamba/Clarence River
- ☐ Coffs Harbour
- ☐ Port Macquarie
- ☐ Wallis Lake
- ☐ Port Stephens
- ☐ Lake Macquarie
- ☐ Newcastle
- ☐ Brisbane Water
- ☐ Pittwater/Hawkesbury
- ☐ Sydney Harbour/Port Jackson
- ☐ Botany Bay
- ☐ Port Hacking
- ☐ Lake Illawarra
- ☐ Jervis Bay
- ☐ Ulladulla
- ☐ Batemans Bay
- ☐ Merimbula
- ☐ Twofold Bay
- ☐ Other (please specify below)

Other estuaries, lakes or ports? Please enter their names here.

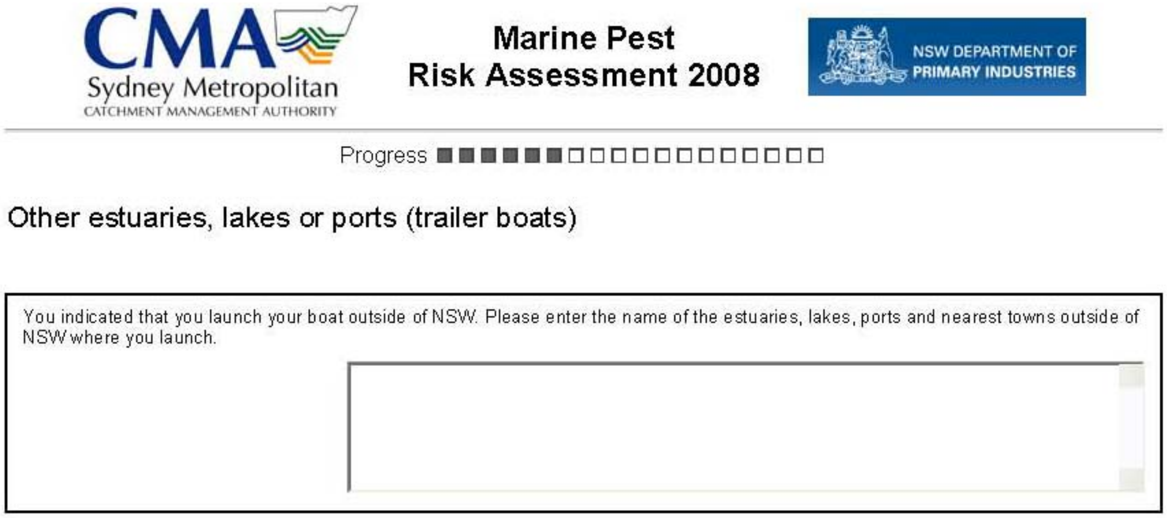


Other estuaries, lakes or ports (trailer boats)

Do you ever launch your boat outside of NSW?

- ○ Yes
- ○ No

Respondents that answer "Yes" are taken to the next page, otherwise the respondent is skipped over the following page.



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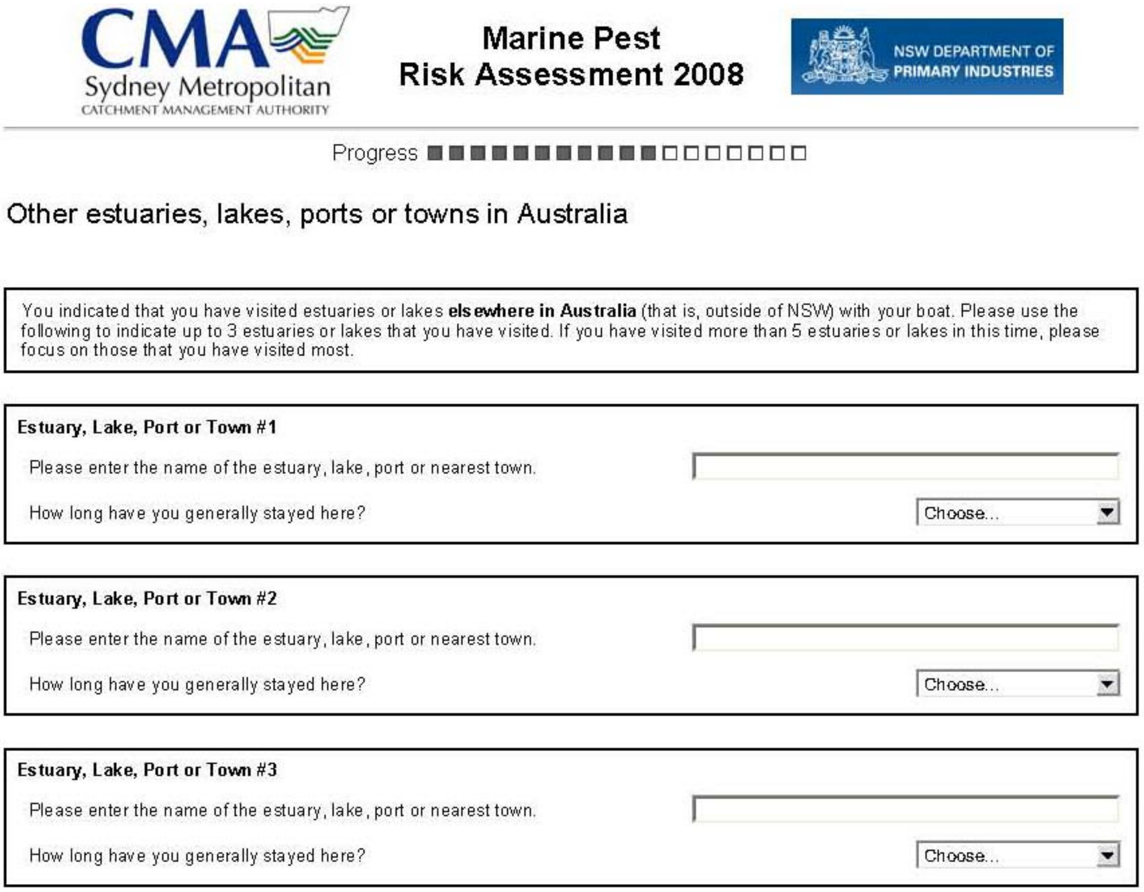
Other estuaries, lakes or ports (trailer boats)

You indicated that you launch your boat outside of NSW. Please enter the name of the estuaries, lakes, ports and nearest towns outside of NSW where you launch.



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Other estuaries, lakes, ports or towns in Australia

You indicated that you have visited estuaries or lakes **elsewhere in Australia** (that is, outside of NSW) with your boat. Please use the following to indicate up to 3 estuaries or lakes that you have visited. If you have visited more than 5 estuaries or lakes in this time, please focus on those that you have visited most.

Estuary, Lake, Port or Town #1

Please enter the name of the estuary, lake, port or nearest town.

How long have you generally stayed here? Choose...

Estuary, Lake, Port or Town #2

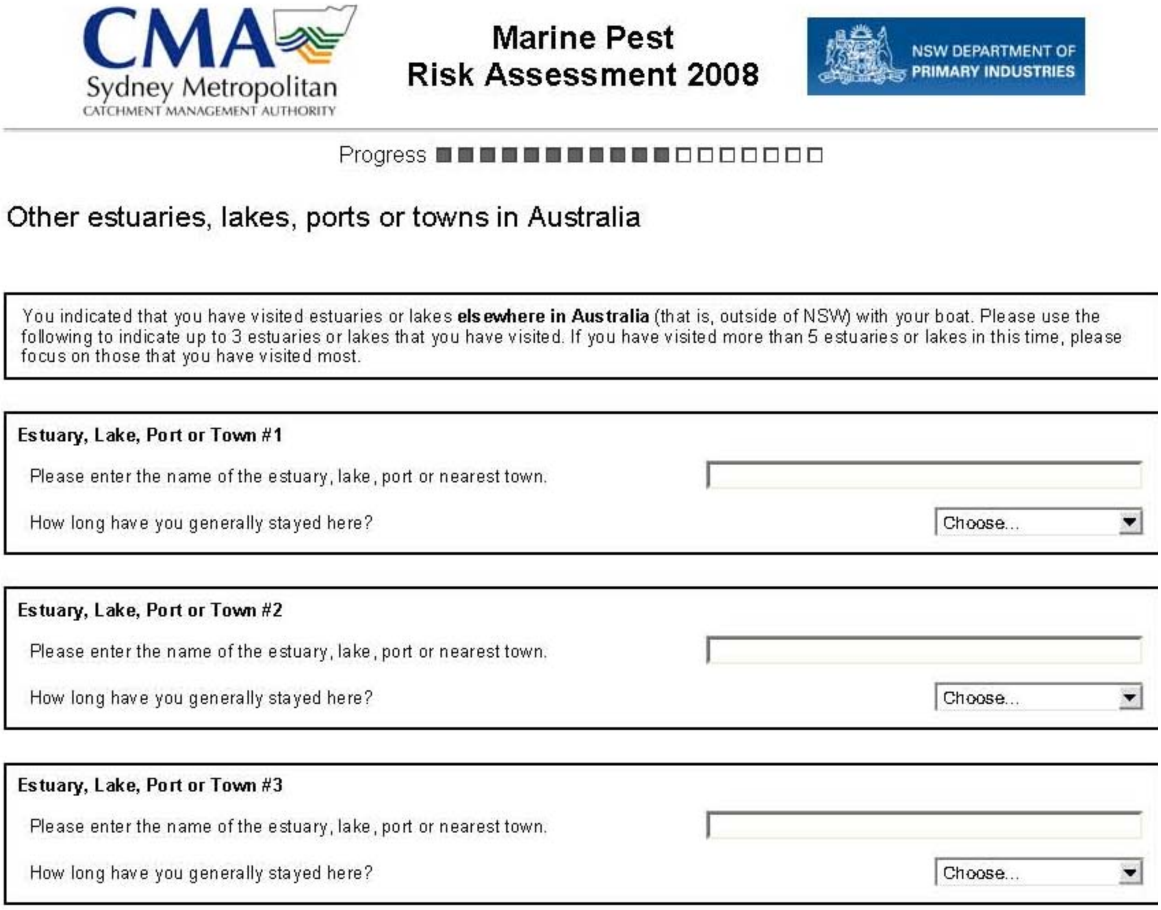
Please enter the name of the estuary, lake, port or nearest town.

How long have you generally stayed here? Choose...

Estuary, Lake, Port or Town #3

Please enter the name of the estuary, lake, port or nearest town.

How long have you generally stayed here? Choose...



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Other estuaries, lakes, ports or towns in Australia

You indicated that you have visited estuaries or lakes **elsewhere in Australia** (that is, outside of NSW) with your boat. Please use the following to indicate up to 3 estuaries or lakes that you have visited. If you have visited more than 5 estuaries or lakes in this time, please focus on those that you have visited most.

Estuary, Lake, Port or Town #1

Please enter the name of the estuary, lake, port or nearest town.

How long have you generally stayed here? Choose...

Estuary, Lake, Port or Town #2

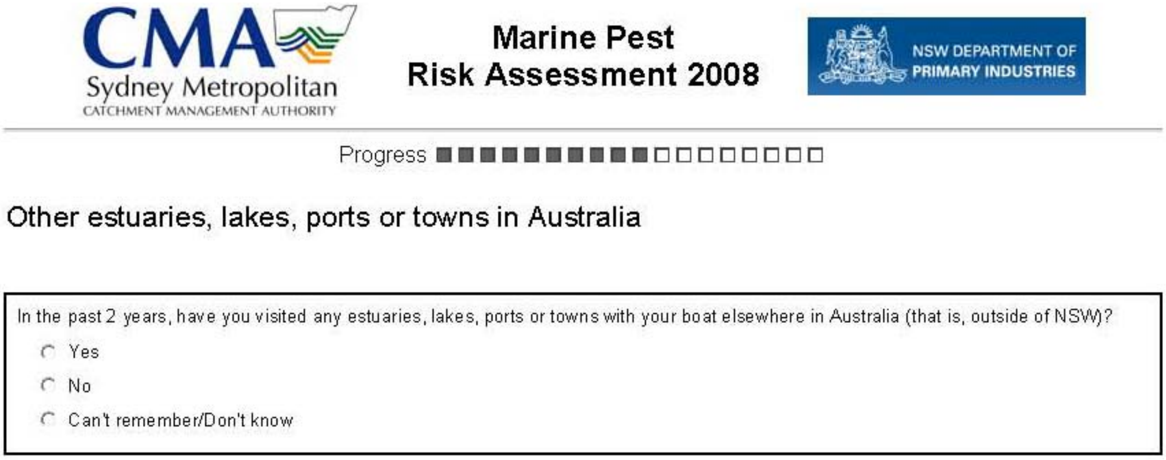
Please enter the name of the estuary, lake, port or nearest town.

How long have you generally stayed here? Choose...

Estuary, Lake, Port or Town #3

Please enter the name of the estuary, lake, port or nearest town.

How long have you generally stayed here? Choose...



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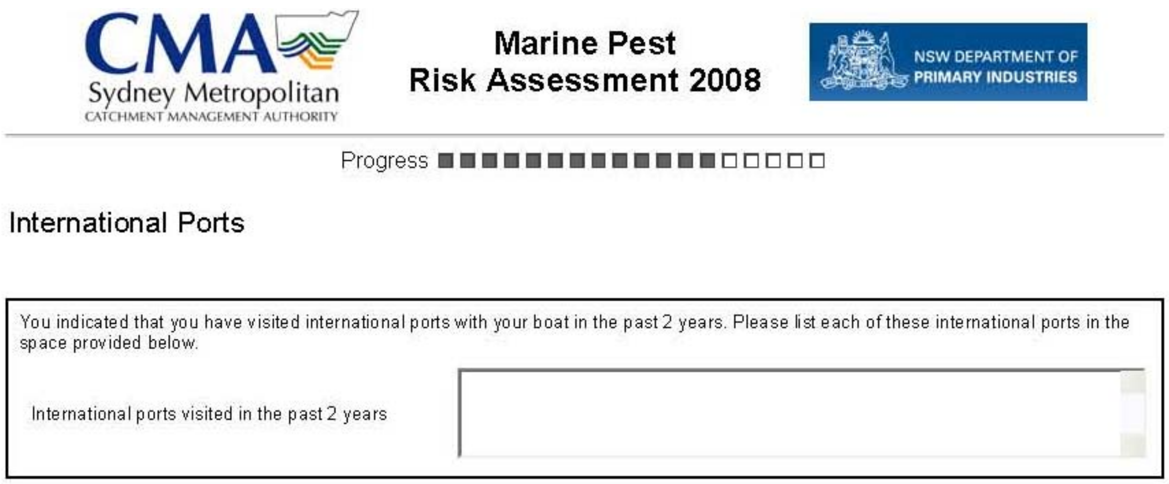
Other estuaries, lakes, ports or towns in Australia

In the past 2 years, have you visited any estuaries, lakes, ports or towns with your boat elsewhere in Australia (that is, outside of NSW)?

○ Yes
○ No
○ Can't remember/Don't know

Respondents that answer "Yes" are taken to the next page, otherwise the respondent is skipped over the following page.



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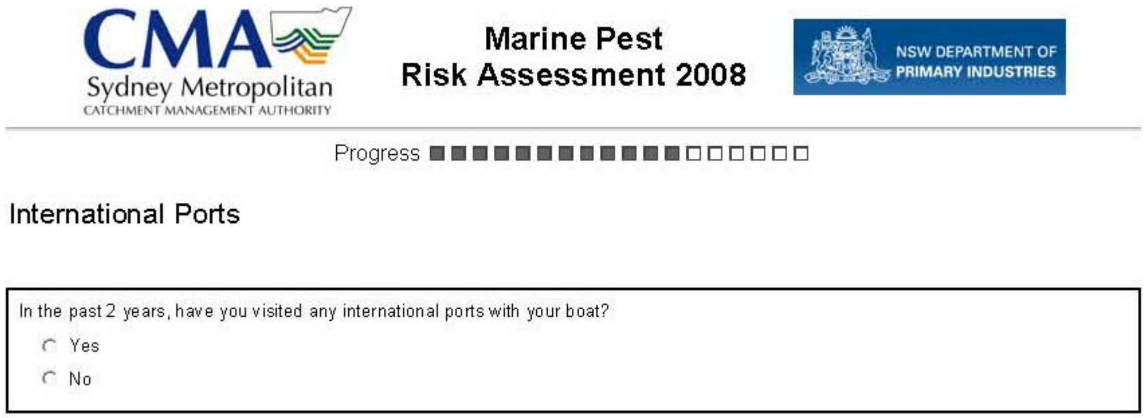
International Ports

You indicated that you have visited international ports with your boat in the past 2 years. Please list each of these international ports in the space provided below.

International ports visited in the past 2 years



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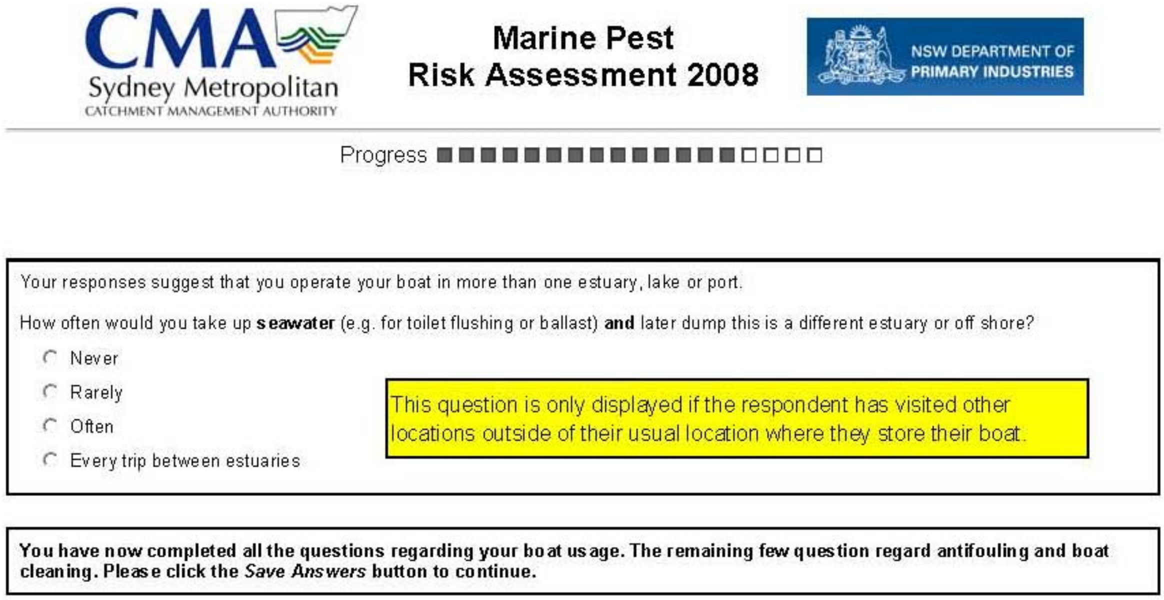
International Ports

In the past 2 years, have you visited any international ports with your boat?

○ Yes
○ No

Respondents that answer "Yes" are taken to the next page, otherwise the respondent is skipped over the following page.



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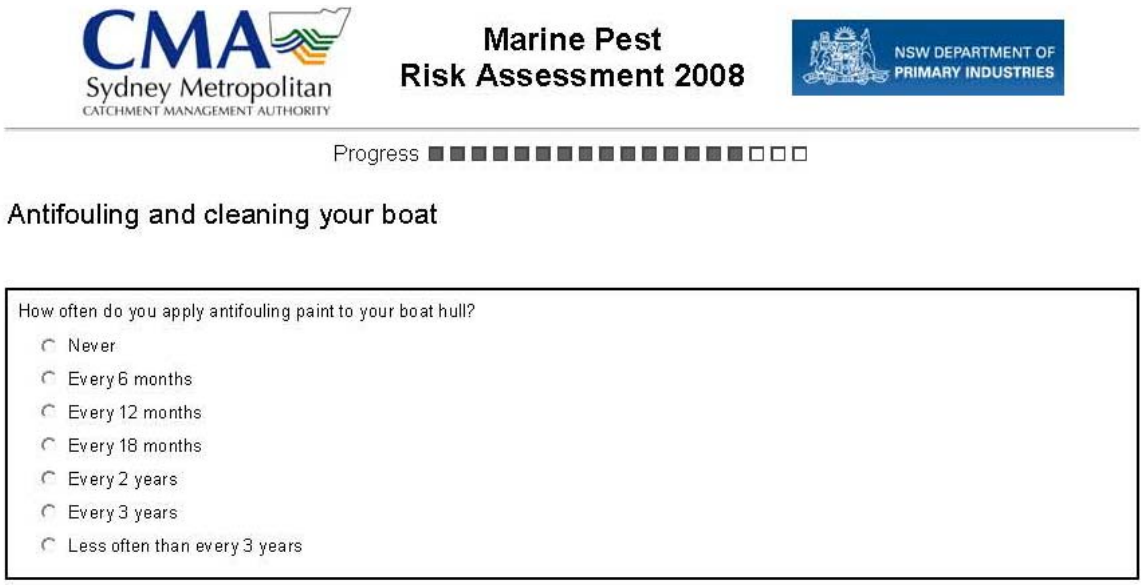
Your responses suggest that you operate your boat in more than one estuary, lake or port.

How often would you take up **seawater** (e.g. for toilet flushing or ballast) **and** later dump this is a different estuary or off shore?

○ Never
○ Rarely
○ Often
○ Every trip between estuaries

This question is only displayed if the respondent has visited other locations outside of their usual location where they store their boat.

You have now completed all the questions regarding your boat usage. The remaining few question regard antifouling and boat cleaning. Please click the *Save Answers* button to continue.



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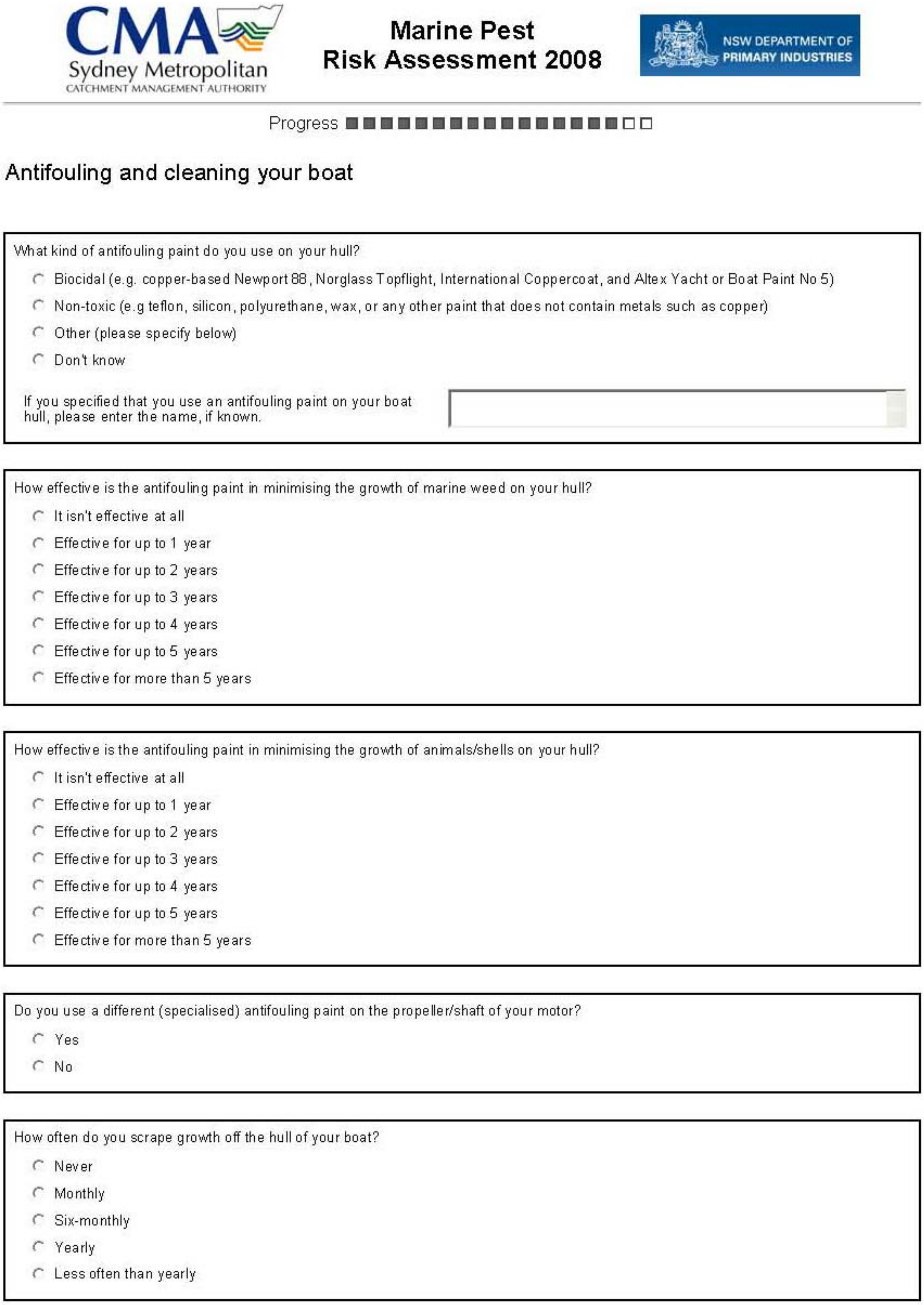
Antifouling and cleaning your boat

How often do you apply antifouling paint to your boat hull?

- ○ Never
- ○ Every 6 months
- ○ Every 12 months
- ○ Every 18 months
- ○ Every 2 years
- ○ Every 3 years
- ○ Less often than every 3 years

Respondents that answer "*Never*" are skipped *to the Comments page at the end of the survey.*



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Antifouling and cleaning your boat

What kind of antifouling paint do you use on your hull?

○ Biocidal (e.g. copper-based Newport 88, Norglass Topflight, International Coppercoat, and Altex Yacht or Boat Paint No 5)
○ Non-toxic (e.g teflon, silicon, polyurethane, wax, or any other paint that does not contain metals such as copper)
○ Other (please specify below)
○ Don't know

If you specified that you use an antifouling paint on your boat hull, please enter the name, if known.

How effective is the antifouling paint in minimising the growth of marine weed on your hull?

○ It isn't effective at all
○ Effective for up to 1 year
○ Effective for up to 2 years
○ Effective for up to 3 years
○ Effective for up to 4 years
○ Effective for up to 5 years
○ Effective for more than 5 years

How effective is the antifouling paint in minimising the growth of animals/shells on your hull?

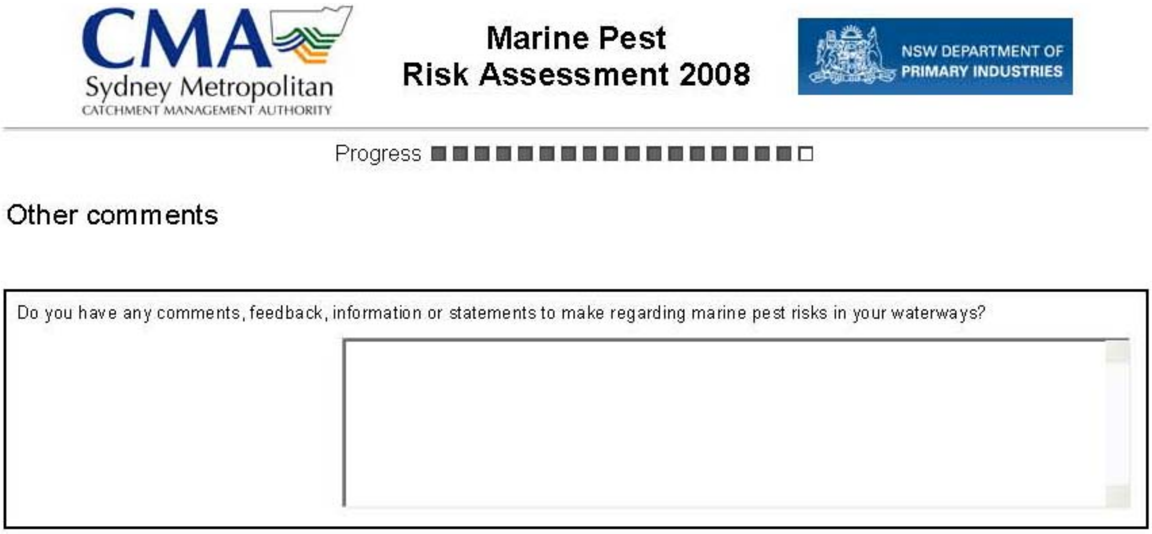
○ It isn't effective at all
○ Effective for up to 1 year
○ Effective for up to 2 years
○ Effective for up to 3 years
○ Effective for up to 4 years
○ Effective for up to 5 years
○ Effective for more than 5 years

Do you use a different (specialised) antifouling paint on the propeller/shaft of your motor?

○ Yes
○ No

How often do you scrape growth off the hull of your boat?

○ Never
○ Monthly
○ Six-monthly
○ Yearly
○ Less often than yearly

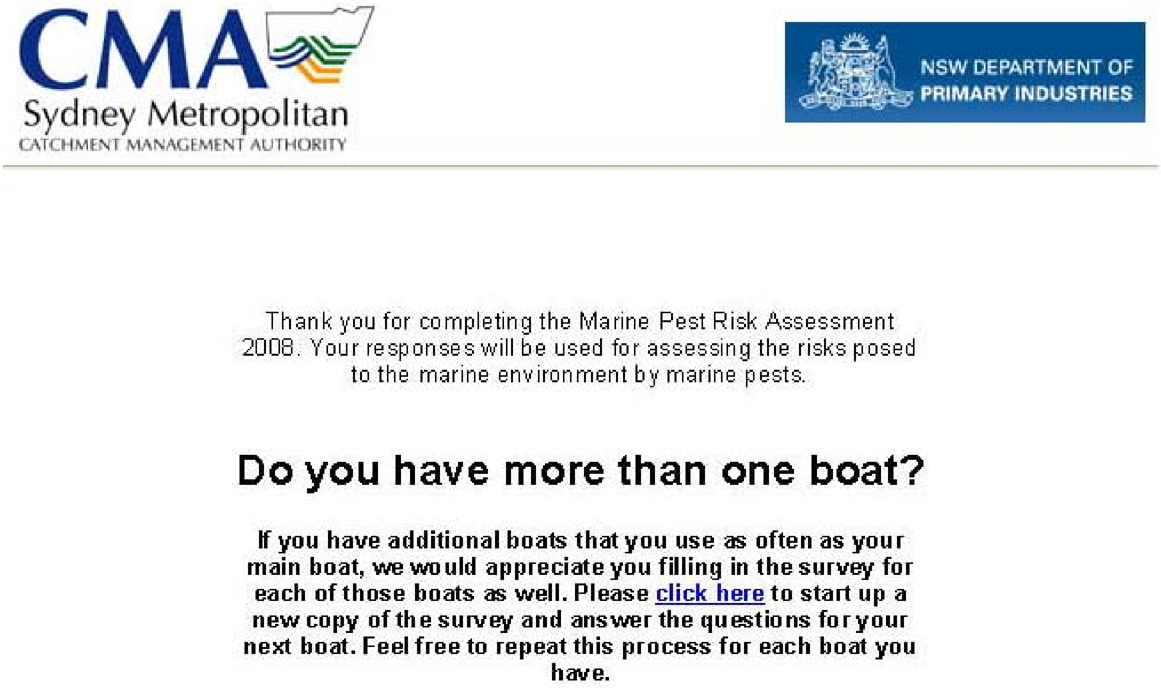


Marine Pest Risk Assessment 2008

Progress ■■■■■■■■■■■■■■■■■■□

Other comments

Do you have any comments, feedback, information or statements to make regarding marine pest risks in your waterways?



Thank you for completing the Marine Pest Risk Assessment 2008. Your responses will be used for assessing the risks posed to the marine environment by marine pests.

Do you have more than one boat?

If you have additional boats that you use as often as your main boat, we would appreciate you filling in the survey for each of those boats as well. Please click here to start up a new copy of the survey and answer the questions for your next boat. Feel free to repeat this process for each boat you have.

Appendix 2. Biological information for marine pests used in this assessment.

Species Name	Tolerance				Normal Range				Reproduction ideals				References
	Salinity (ppt)		Temp (°C)		Salinity (ppt)		Temp (°C)		Salinity (ppt)		Temp (°C)		
	min	max	min	max	min	max	min	max	min	max	min	max	
Potamocorbula amurensis	0	35	0	28	1	33	8	23					1; 2; 3; 5
Eriocheir sinensis	0	35	0	30	15	25	12	18	16	30			4; 46
Sargassum muticum	7	34	-1	30	34	34	10	30	16		8		5; 6; 7; 8; 9
Siganus rivulatus	<10	>50			35		27				>14	<36	10; 11
Mya arenaria	0	50	-2	33	4	32	4	22	8	32	17	23	1; 12; 16; 15; 41
Caulerpa racemosa													
Perna perna	8	55	3	45	19	40	10	30	31	32	10	30	17; 18; 19; 20; 21
Neogobius melanostomus		41	-1	30	1	19	16	27	4	20	9	26	22, 23, 25 in 24; 24
Hemigrapsus takanoi/penicillatus					7	35	13	20					26
Perna viridis	0	80	6	38	18	33	11	32				33	28; 10; 17; 30, 31, 33, 34 in 35; 36
Hemigrapsus sanguineus	8	33	1	27	29	33	1	27	15		15		38; 39; 40
Didemnum vexillum/lahillei	26		-2	24	7	35	5	28					5; 13
Mnemiopsis leidyi	2	38	1	32	0	33	6	30					13; 43; 44 in 47; 45 in 47
Ensis directus	30	40			10	33	16	30					13; 41
Crepidula fornicata	18	40	0	35	24	33	6	20			10		41; 42; 52
Rapana venosa	9	39			18	28	4	27	14	20	13	26	46; 55; 56; 57
Marenzelleria wireni			-2	34	16	32							37; 62
Charybdis japonica			4	34	28	33					20	28	63; 64
Mytilopsis sallei	0	50	5	40	22	32	18	30					65; 66; 67; 68
Perna canaliculus					23	35	10	19					69
Caulerpa taxifolia	10	80	9	33	27	36	12	25					70; 71; 72
Carcinus maenas	4	54	0	33	20	33	6	26	20		18	26	5; 27; 29; 73; 74 in 75
Sabella spallanzanii							11	29			11	14	76
Codium fragile ssp. *tomentosoides*	12	40	-1	35	24	30	10	30					41; 77; 78
Maoricolpus roseus							8	20					14
Musculista senhousia	7	39	-3	36	17	37	16	33		30	22	28	5; 41; 79 in 85; 80; 81 in 53; 82
Undaria pinnatifida	20	34	0	30	29	34	5	11			10	20	41; 53; 83; 84
Varicorbula gibba	0	34	-1	26	28	34	1	16					58; 61; 59, 60 in 53
Asterias amurensis	24	35	0	>30	24	35	3	34	28	35	8	20	
Grateloupia turuturu	12	52	4	28	22	37	6	28					

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