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How useful are port surveys focused on target pest identification for exotic species management?

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ABSTRACT

Monitoring surveys are an important tool for detecting new arrivals of exotic species, for documenting patterns of invasion, and exotic species impacts. Faced with time and cost constraints, these surveys are increasingly focused on lists of target pest species, identified as being most likely to arrive and cause significant harm. We used the national survey of Australian international ports for introduced marine pests as a case study to assess: (1) the taxonomic rigor of surveys focused on detection of target species; and (2) how the ability of port surveys to inform invasion patterns is dependent on taxonomic approach. Our analysis of the 46 available reports revealed common sub-optimal taxonomic practices that compromised their utility to identify abiotic conditions that are good predictors of biological invasion. Thus, although surveys for target species may provide information on the distribution of a handful of species, they may fail to do much else.

1. Introduction

Exotic species represent a major threat to the ecological, economic and social value of marine environments (Lubchenco et al., 1991; Molnar et al., 2008). In recognition of this threat, many countries have developed exotic marine species management programs (see Hewitt et al., 2009). A large part of these management programs is the prevention of new introductions of exotic species. Yet with even the best prevention strategies, some new introductions are inevitable. Consequently, the programs must also include a framework for rapidly detecting and effectively managing new arrivals of exotic species.

Monitoring surveys are integral to the effective management of new arrivals of exotic species. They can: (1) provide a detection system for target pest species, facilitating the opportunity for their eradication before proliferation and spread; (2) provide a baseline of native and exotic biodiversity, against which future arrivals may be assessed; (3) assess invasion patterns relative to abiotic and biotic factors; and (4) provide information on impacts of invasions. The effectiveness of monitoring surveys in providing these services is, however, dependent on their design. For example, whether only non-native or both non-native and native species are sampled, whether abundance or presence–absence data are collected, with what intensity and frequency habitats are sampled, and the level of taxonomic resolution and accuracy can influence the information the survey can provide (Lee et al., 2008).

Increasingly, target 'next pest' species lists are informing the design and conduct of monitoring surveys (e.g. Campbell et al., 2007; Minchin, 2007). Target 'next pests' are those exotic species that are not yet present (or at least not widespread) in a particular marine jurisdiction, but that have been identified as being the most likely to establish in the near future and produce major impacts. 'Next pests' are commonly identified using criteria such as whether the species: (1) has a vector that is prevalent in the marine jurisdiction (i.e. ships); (2) has caused environmental and/or economic harm elsewhere; and (3) is exotic to the marine jurisdiction or, if present, subject to official control or restricted to a defined and manageable area (Hayes and Sliwa, 2003). The lists are often compiled and modified in an arbitrary and inaccurate manner (Sliwa et al., 2009). Rarely do they take into biotic or physical attributes of the recipient environment that may affect invasion success (e.g. native species diversity – Stachowicz et al., 1999; grazing, competition and predation – Levine et al., 2004; properties of the local environment – Byers, 2002).

The use of target pest species lists by monitoring studies could compromise the management of exotic species introductions if this approach is at the expense of detecting other, unanticipated, arrivals. 'Non-target' exotic species could go undetected if: (1) survey methods are specific to the target taxa; (2) only the presence–absence of the target taxa are documented; and/or (3) the surveys utilize parataxonomists, trained to identify the target pest species, but poorly equipped to distinguish other exotic species (i.e. those

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not previously reported from the region) from native taxa. Without full documentation of all exotic and native species present at a site, the survey may be of little value as a baseline against which to assess future arrivals, as a data point in determining spatial patterns of invasion and as a source of information for developing studies to determine impacts of exotic species introductions.

Here, we use the Australian port surveys (completed 1995–2004) as a case study with which to investigate the usefulness of monitoring surveys focused on target pest lists for exotic species management. Specifically, we consider: (1) the taxonomic rigor of such monitoring surveys; and (2) their utility as a baseline against which to detect future arrivals, inform patterns of invasion and invasion impacts. This case study was chosen because the protocols used by the Australian port surveys have acted as a benchmark for the majority of port surveys for marine bioinvasions undertaken globally (Campbell et al., 2007). Consequently, these issues are likely to be common to surveys done elsewhere.

2. The Australian ports surveys

The Australian ports surveys were initiated in 1996 to assess the distribution of exotic species in Australian ports. In recognition that a large number of agencies and research organisations would conduct the surveys, a standard set of protocols were developed that could be applied to each of Australia's over 70 international shipping ports (see Campbell et al., 2007). The protocols prescribed the quantitative and qualitative methods that should be used to detect rare species (including sampling methods and effort) and included a list of exotic species to be targeted. The target species were: (1) the 12 listed on the Australian Ballast Water Management Advisory Council's (ABWMAC) schedule of target introduced pest species; (2) a group of species which are major pests in overseas ports and which, on the basis of their invasive history and projected shipping movements, might be expected to colonize Australian Ports; and (3) those known exotic species in Australian waters that are currently not assigned pest status (Appendix A). Although the surveys targeted designated species, it was also intended that they would provide information on the distribution of other exotics, cryptogenic species (of unknown origin) and native species within ports (Campbell et al., 2007). These goals required accurate identification of specimens to species level. Samples were collected from the ports and processed by a range of contractors.

3. Methods

We obtained all available final reports for completed Australian port surveys (n = 46, Table 1, Fig. 1) and assessed: (1) the taxonomic approach taken by each and (2) how the conclusions that could be collectively drawn from the reports on biodiversity and patterns of invasion were dependent on the level of taxonomic rigor.

3.1. The taxonomic approach employed by the surveys

We evaluated the taxonomic approach of each port survey according to: (1) the level of taxonomic expertise (see definition below) employed in identifying specimens of each group (phyla/orders); (2) the proportion of specimens identified to species level; and (3) whether native as well as introduced species were documented. We defined 'expert identification' as either classification by someone who: (1) has published on the taxonomy of the group in question (and hence has access to a network of world experts on that group); (2) is working under the direct supervision of someone who has published on the taxonomy of the group; or (3) has access to verified reference specimens of the group in question, and has sufficient experience to be able to use these effectively. We separately assessed the extent to which inherent taxonomic difficulties, beyond the control of the national project, might compromise the fulfilment of port survey goals. Specifically we considered: (1) how many of the taxa documented as exotic also have native species in the same genera; and (2) the proportion of reports documenting species new to science or new to Australia, and that consequently are difficult to classify as either exotic or native.

3.2. The ability of the port surveys to inform patterns of invasion

To assess the extent to which port surveys employing lower taxonomic effort could inform patterns of invasion, we conducted two case studies using the Australian port surveys data. The first considered whether patterns of among-port dissimilarity in species 'invasion' are dependent on taxonomic approach. The second ascertained whether such a taxonomic approach influences conclusions about the subset of abiotic variables best describing national patterns of invasion.

Each of the case studies utilized information extracted from the reports on the target, other exotic and cryptogenic (not demonstrably native or exotic; Carlton, 1996) species detected at each port. Although not all cryptogenic species may be exotic, they are frequently treated as such in analyses, and we wanted to ascertain the effect of this practice. The second case study also used data on the physical and anthropogenic environment of each port, including: (1) latitude; (2) longitude; (3) minimum water temperature; (4) maximum water temperature; (5) minimum salinity; (6) maximum salinity; (7) spring tidal range; and (8) number of shipping berths (an indicator of shipping activity; Table 1). This was obtained from the reports, the Australian Bureau of Meteorology and the Association of Australian Ports and Marine Authorities Incorporated. The first case study utilized the 45 Australian ports for which we had records of target, exotic and cryptogenic species. The second utilized a subset of these (n = 33), for which we could also obtain a full abiotic data set.

To assess the robustness of spatial patterns of invasion to a taxonomic approach, we tested for correlations between among-port dissimilarity matrices that had been constructed using: (1) only target pest species; (2) target pest species and known exotics; and (3) target pest species, exotic species and cryptogenics. Matrices were constructed of Bray–Curtis dissimilarity measures calculated using presence–absence data. Presence–absence rather than abundance data were used because: (1) this severe transformation is recommended where communities contain many rare species, the effects of which would otherwise be swamped by more common species (Clarke and Warwick, 2001); and (2) not all of the data collected by the port surveys were quantitative (at some ports, a presence–absence approach was used for documenting some taxa). The Bray–Curtis dissimilarity measures were zero-adjusted for denuded assemblages by adding a dummy variable that was universally present across all ports to the presence-absence data matrix (see Clarke et al., 2006). Spearman's rank correlations between pairs of matrices were done using the RELATE procedure of PRIMER (Clarke and Warwick, 2001).

To assess whether the abiotic variables best describing national patterns of species invasion vary according to the taxonomic approach employed, we used the BIO-ENV procedure of the PRIMER package (Clarke, 1993). The BIO-ENV procedure sequentially determines the rank correlation between the biotic dissimilarity matrix and abiotic dissimilarity matrices based on all possible combinations of abiotic variables, and at all possible levels of complexity (here, 1–8; Clarke and Ainsworth, 1993). For each of the three Bray–Curtis matrices of among-port dissimilarity in exotic biota,

Table 1
Summary of the Australian port surveys included in analyses. NA, data not available. Locations of ports are shown in Fig. 1.

	Port	Latitude	Longitude	Province	Morphology	Water temp. (°C)	Salinity (ppt)	Tidal range (m)	Shipping berths (#)	Exotic spp. (#)	Crypt. spp. (#)	Native spp. (#)
1.	Cape Flattery	14.98°S	145.35°E	Solanderian	Peninsula	22–32	34–35	2.4	1	0	7	877
2.	Cairns	16.93°S	144.78°E	Solanderian	Estuary	20–32	5–34	3.4	11	3	2	1303
3.	Mourilyan	17.58°S	146.08°E	Solanderian	Estuary	25–33	1–35	3.5	1	2	4	395
4.	Lucinda	18.52°S	146.32°E	Solanderian	Deltaic channel	21–31	21–35	4.0	2	2	9	469
5.	Townsville	19.25°S	146.83°E	Solanderian	Estuary	19–32	25–36	4.1	9	0	11	1193
6.	Abbot Point	19.88°S	148.08°E	Solanderian	Coastal embayment	19–32	24–36	3.5	1	0	4	589
7.	Mackay	21.12°S	149.23°E	Solanderian	Coastal embayment	18–30	NA	6.4	5	1	10	367
8.	Hay Point	21.25°S	149.30°E	Solanderian	Peninsula	20–30	35–37	7.1	4	3	7	496
9.	Gladstone	23.83°S	151.58°E	Solanderian	Estuary	20–28	35–42	4.7	12	10	0	281
10.	Lord Howe Is	31.50°S	159.08°E	Lord Howe	Shelf island	17–25	NA	1.5	0	17	2	574
11.	Newcastle	32.93°S	151.78°E	Peronian	Estuary	12–25	21–35	1.9	20	10	21	437
12.	Sydney	33.86°S	151.24°E	Peronian	Estuary	16–22	36	2.0	0	18	10	414
13.	Botany Bay	34.00°S	151.23°E	Peronian	Estuary	16–22	33–35	1.9	6	34	18	339
14.	Port Kembla	34.47°S	150.90°E	Peronian	Coastal lagoon	15–21	35–36	1.9	14	36	14	461
15.	Eden	37.08°S	149.94°E	Peronian	Coastal embayment	15–25	NA	2.0	4	13	11	87
16.	Flinders Is	40.22°S	148.23°E	Maugean	Shelf island	NA	NA	3.1	2	3	3	320
18.	Spring Bay	42.53°S	147.91°E	Maugean	Coastal embayment	9–20	35–36	1.3	1	28	24	300
17.	Bridport	41.00°S	147.40°E	Maugean	Estuary	NA	NA	3.1	1	2	0	NA
19.	Hobart	42.88°S	147.33°E	Maugean	Estuary	NA	23–35	1.5	8	41	27	350
20.	Kettering	43.13°S	147.25°E	Maugean	Coastal embayment	NA	NA	1.5	0	16	21	166
21.	Dover	43.33°S	147.70°E	Maugean	Deltaic channel	NA	NA	1.5	0	7	0	NA
22.	Port Davey	43.61°S	146.84°E	Maugean	Estuary	NA	NA	1.5	0	3	6	259
23.	Strahan	42.16°S	145.33°E	Maugean	Estuary	NA	NA	1.5	0	1	0	NA
24.	Stanley	40.77°S	145.31°E	Maugean	Peninsula	11–18	35–36	3.0	1	21	0	NA
25.	Burnie	41.05°S	145.92°E	Maugean	Coastal embayment	11–18	34–36	3.1	5	14	27	477
26.	Devonport	41.18°S	146.37°E	Maugean	Estuary	10–20	30–34	3.2	8	8	2	259
27.	Launceston	41.02°S	146.75°E	Maugean	Estuary	10–20	25–36	3.3	11	15	14	534
28.	St. Helens	41.32°S	148.25°E	Maugean	Coastal embayment	NA	NA	1.3	0	9	2	NA
29.	Grassy	40.06°S	144.06°E	Maugean	Shelf island	NA	NA	1.5	3	2	11	332
30.	Hastings	38.38°S	145.22°E	Flindersian	Coastal embayment	10–22	30–38	2.8	5	7	0	349
31.	Melbourne	38.08°S	144.92°E	Flindersian	Estuary	11–19	10–35	0.7	31	29	8	279
32.	Geelong	38.08°S	144.38°E	Flindersian	Coastal embayment	9–23	27–39	0.9	15	20	0	294
33.	Portland	38.38°S	141.61°E	Flindersian	Coastal embayment	11–21	35–36	1.1	6	9	0	253
34.	Adelaide	34.85°S	138.50°E	Flindersian	Estuary	22–28	37–41	2.4	19	15	4	384
35.	Port Lincoln	34.72°S	135.83°E	Flindersian	Coastal embayment	13–19	35–36	1.8	10	9	8	107
36.	Esperance	31.85°S	121.88°E	Flindersian	Coastal embayment	16–23	35–36	1.0	3	19	18	324
37.	Albany	35.03°S	117.90°E	Flindersian	Coastal embayment	16–22	36–37	1.0	4	11	0	162
38.	Bunbury	33.32°S	115.65°E	Flindersian	Coastal embayment	16–23	23–37	1.0	6	14	3	NA
39.	Fremantle	32.03°S	115.73°E	Flindersian	Estuary	17–23	5–36	1.2	14	6	6	707
40.	Geraldton	28.77°S	114.43°E	Dampierian	Coastal embayment	19–25	35–36	1.0	6	8	24	72
41.	Port Headland	20.32°S	118.57°E	Dampierian	Coastal embayment	20–31	34–35	5.8	5	4	3	499
42.	Darwin	12.47°S	130.83°E	Dampierian	Estuary	23–31	29–35	8.0	5	1	3	879
43.	Gove	12.27°S	136.82°E	Dampierian	Peninsula	23–30	34–35	3.0	4	NA	NA	NA
44.	Karumba	17.50°S	140.83°E	Dampierian	Deltaic channel	15–32	0–39	4.8	1	0	5	430
45.	Weipa	12.58°S	141.60°E	Dampierian	Estuary	24–32	27–38	3.2	4	1	13	564
46.	Thursday Is	10.55°S	142.26°E	Dampierian	Shelf island	24–28	22–36	3.9	3	0	0	778

we ascertained the subset of abiotic variables that needed to be input into a Euclidean distance matrix to produce the best rank correlation. We determined whether this subset differed among the three taxonomic approaches.

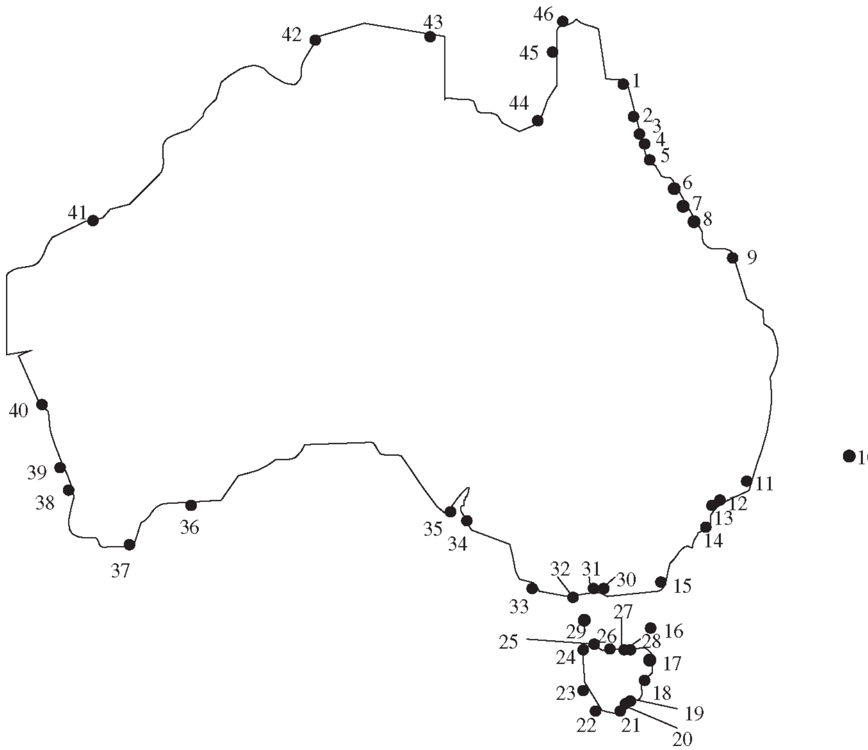

Fig. 1. Map of Australia showing the location of the 46 ports for which survey reports and data were available for analysis. Numbers correspond to those shown in Table 1.

4. Results and discussion

4.1. The taxonomic approach of the surveys

Our analysis of the 46 available reports from the Australian port surveys revealed common sub-optimal taxonomic practices (summarised in Table 2).

Of the reports, only one employed expert identification of all groups (Table 2). Some primarily utilized parataxonomists, but most included a mixture of approaches. Some taxonomic groups, such as bryozoans and microalgae, were consistently expert-identified across almost all (>90%) ports. Others taxa were poorly handled despite the groups having practising taxonomists within Australia (e.g. polychaetes where only 54% of surveys utilized expert identification, as defined above). For several (nemerteans, ascidians, hydroids and sipunculans), adequate taxonomic expertise could not be found within the Australian workforce, and maintenance of taxonomic rigor required drawing upon the skills of retired experts or seeking advice from outside of Australia.

In over half of the reports, the groups in which taxa were not identified to species exceeded 50%. The post-collection sorting and identification of specimens was generally focused on those families and genera containing the national target species. Although, faced with tight budgets and time constraints, compromises are often necessary, focusing effort solely on groups known to contain exotics raises the possibility that new exotics, previously unknown to have invaded a region, could go undetected. Invaders have been found in a broad range of invertebrate and vertebrate groups. Given that early detection of new invaders is critical for their successful management and is one of the primary goals of port surveys, focusing on known exotics consequently limits the value of port surveys. Furthermore, focusing on exotics already known to an area can be counterproductive because many of these have already proliferated to population sizes that cannot be eradicated or controlled.

Table 2
Common problems and difficulties associated with the documentation of introduced species at Australian ports.

Common taxonomic problems among the 46 final reports of port surveys
• Failure to employ expert assistance for identification of all phyla/divisions: 98%
• Native species not documented: 10%
• Failure to consider that new species records may represent undescribed native species and not introduced species: 22%
Inherent difficulties associated with port surveys
• Introduced species detected in surveys with cogeneric natives: 49%
• Of these, those with >1 cogener: 55%
• Surveys recording species new to science: 21%
• Surveys recording species not previously known from Australia: 29%
• Ports for which no baseline data is available: 43%

Most reports documented native as well as exotic species, but 10% did not (Table 2). This undermines the value of port surveys as baseline studies. Without a full description of native species, future studies will not be able to confidently distinguish between what is exotic and what is native (Hutchings et al., 1987; Pollard and Hutchings, 1990). Although the biodiversity of many Australian regions is poorly known, several of the reports failed to consider that new records of a species in Australia might not necessarily represent invasions but, instead, natives that had previously been described (Table 2).

The sub-optimal taxonomic practices were compounded by two main intrinsic taxonomic difficulties.

First, many (almost 50%; Table 2) exotic marine species within Australia had at least one native species within their genus. For example, the exotic crab *Petrolisthes elongatus* from New Zealand had 16 native species in its genus. Particularly in this and other instances in which the number of co-geners is greater than one (55%; Table 2), the taxonomic similarity of native and exotic species makes their discrimination all the more difficult and in many instances contingent on consultation with an expert on that taxonomic group. Distinction between even closely related exotic and native species is important given that they may play very different

Table 3
Robustness of among-port patterns of invasion to the level of taxonomic scrutiny employed. Robustness was assessed by calculating Bray–Curtis dissimilarity matrices of among-port differences using: (1) all exotic and cryptogenic species (All); (2) only demonstrably exotic species (E); and (3) only ABWMAC target species (T), and then examining the degree to which the three matrices were correlated using the RELATE routine of PRIMER (Clarke and Warwick, 2001). Significance levels (Sig.) of less than 5% denote that matrices that were statistically correlated.

Comparison	Rho	Permuted statistics > rho	Sig. (%)
All v. E	0.83	0	0.1
All v. T	0.64	0	0.1
E v. T	0.44	0	0.1

roles in ecological communities (see Bishop and Peterson, 2006, for a consideration of ecological differences between oysters of the genus *Crassostrea*). Given the cosmopolitan nature of marine taxa, this problem is likely to be common to all regions of the world.

Second, because Australia does not have a long history of the natural sciences and has a large area of unstudied coastline, in many instances it was very difficult to discriminate between what is native and what is exotic. The vast majority (43 out of 46) of the Australian ports considered had not previously been surveyed. Consequently, 21% of the surveys reported species new to science and 29% reported species not previously known to Australia. Whether these are native species that had not previously been detected due to low sampling effort or are recently arrived exotics it may not be possible to ascertain without costly and time consuming molecular analyses of Australian and overseas populations (e.g. Luikart and England, 1999). This problem is likely to be common to many of the world's most biodiverse regions, which are situated in developing nations without a long tradition of taxonomy. This problem further highlights the necessity of documenting all native and exotic taxa present at surveyed ports, so that there is a baseline against which to compare the results of subsequent surveys. Ideally this material should be deposited in a local museum which can be referred to in future studies and checked for taxonomic correctness.

4.2. The ability of the port surveys to inform patterns of invasion

From our analyses, it is apparent that there is substantial variation among surveys in the level of taxonomic scrutiny employed. Analyses indicated that on a national level, spatial patterns of invasion among ports were robust to this variation in taxonomic approach. Matrices of Bray–Curtis dissimilarities among ports were significantly correlated with one another, irrespective of whether they were constructed using only target species, all exotic species, or all exotic and cryptogenic species (Table 3). Subsets of abiotic variables best predicting broad geographic patterns of invasion were, by contrast, contingent on the level to which exotic species were resolved. When all exotic and cryptogenic species were included in the analysis, latitude alone was the best predictor of the invasive species present ($\rho = 0.507$). When cryptogenics were excluded, latitude was also found to be the best predictor, although the relationship was slightly weaker ($\rho = 0.427$). If, however, only target species were included in the analysis, minimum water temperature and number of shipping berths were also required to predict spatial patterns ($\rho = 0.321$). Hence, using information about drivers of target species distributions to develop strategies for managing new species invasions might not be an appropriate approach.

5. Conclusions and recommendations

The Australian port surveys represented an international first. They covered the majority of Australia's ~72 widely distributed shipping ports, using standardized sampling protocols designed to maximize the likelihood that exotic marine species were detected. For many of Australia's ports, particularly those in tropical areas, this was the first time they had ever been surveyed. In several instances, new invaders were detected early, and following the prompt implementation of management plans, one – the black striped mussel, *Mytilopsis* sp. – was successfully eradicated (Bax et al., 2002). In recognition of the value that well-designed port surveys can have in serving as an early-warning system for the arrival of costly pests, the Australian port surveys protocols have now been adopted by a number of other governments and NGOs (see Campbell et al., 2007).

Yet although the Australian port survey appeared to meet its first goal of providing a system for detection of the 12 ABWMAC-listed target pest species, overall it did not provide a comprehensive picture of marine bioinvasions in Australia. Focus on target pest species was, in many instances, at the expense of documenting the distribution and abundance of other exotic taxa. Several of the surveys only identified taxa to species in the families and genera containing target pests. Moreover, sampling methods were developed based upon the biology of target species and were not necessarily appropriate for detecting other exotic taxa. The focus of surveys on target pest species and their close relatives compromised their ability to provide useful information on the abiotic factors that are good predictors of spatial patterns of invasion. Our analyses indicated that the suite of environmental variables that best explained spatial patterns of target species invasion was different to the single variable, latitude, that best explained invasion of a more comprehensive set of invaders, including non-target species.

Many of the surveys relied heavily on parataxonomists, often inadequately trained to accurately distinguish congener native and exotic taxa. Consequently even where native and non-target exotic species were documented, the accuracy of this information is questionable. Taxonomic difficulties appear to extend to the correct identification of some of the target pest species. Recent research on Sabellids has found that some previously undescribed native species had been incorrectly labelled as *Sabella spallenzanii* (Capa, unpublished data). The lack of a national system for species archival means that the accuracy of many of the records cannot be verified.

On top of taxonomic issues resulting from a focus of the surveys on target pest species, the surveys also suffered from their snapshot approach. With the exception of the port of Darwin that was sampled in the wet and the dry season (Russell and Hewitt, 2000), the other ports were only sampled on a single date. This means that invaders displaying seasonality in their life cycles may well have been missed. With the surveys costing an estimated AUS$ 6 million, there are no immediate plans for revisiting sites.

It is clear that in an ideal world, port surveys would involve collection of large numbers of specimens across multiple times, they would employ experts to identify all specimens to species, and register voucher specimens at local museums. Yet the question remains how can this be done cheaply and in a world with declining taxonomic expertise? We suggest the answer is twofold.

First, we need to move beyond traditional monitoring approaches and harness new technologies that are less labour-intensive and enable cheap processing of samples in the laboratory (Lodge et al., 2006). Molecular tools are already proving to be extremely useful for the detection of small amounts of exotic species DNA in large water samples (Darling and Tepolt, 2008). In combination with remote sensing, that can help identify habitats more vulnerable to invasion (Chong et al., 2001), they could form the basis of rapid and effective monitoring programmes.

Second, we need to recognise that it is very costly to survey a port properly and be more selective of the ports we sample. When developing port surveys or undertaking additional surveys, funds must not only be allocated for the collection of material but also for its sorting, identification and archiving for posterity. To ensure provision of accurate baseline data and of voucher collections for future assessments of marine biodiversity, funding should be available to identify (to species) and archive all specimens. Given that rigorous sampling is extremely costly, rather than sampling every port and having to stop at identification of target species, it would be better to strategically select a few ports, based on their vulnerability or proximity to critical habitats, and to sample comprehensively. Intensive and comprehensive sampling has been effectively used in Port Phillip Bay to document the bay's invasion history over 150 years (Hewitt et al., 2004).

In summary, our study has highlighted how the focus of port surveys on target pest species can erode their value. In the absence of an approach that enables accurate identification of all taxa to species, surveys will be of little value in the management of exotic species and may instead provide misleading and inaccurate information. Given limited taxonomic and financial resources, surveys will need to be increasingly creative in their use of new technologies.

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Appendix A

Taxa on which the Australian port surveys focused due to either: (1) their inclusion on the Australian Ballast Water Management Advisory Council's (ABWMAC) schedule of target introduced pest species; (2) their identification as marine pest species that pose a threat to Australia; or (3) their status as a known or likely introduced species in Australia.

1. **ABWMAC schedule of target introduced pest species**

Gymnodinium catenatum (toxic dinoflagellate)
Alexandrium catanella (toxic dinoflagellate)
Alexandrium minutum (toxic dinoflagellate)
Alexandrium tamarense (toxic dinoflagellate)
Undaria pinnatifida (Japanese seaweed)
Asterias amurensis (northern Pacific seastar)
Sabella spallanzanii (giant fan worm)
Carcinus maenas (European shore crab)
Corbula gibba (European clam)
Mytilopsis sallei (Central American striped mussel)
Musculista senhousia (Asian date mussel)
Crassostrea gigas (Pacific oyster)

2. **Marine pest species that pose a significant threat to Australia**

Mnemiopsis leidyi (North American comb jelly)
Philine auriformis (New Zealand sea slug)
Potamocorbula amurensis (Chinese clam)
Mytilus galloprovincialis (Mediterranean mussel)

3. **Known exotic species present in Australian waters**

ANIMALS
Bougainvillea ramosa (hydroid)
Hydroides elegans (serpulid)
Boccardia proboscidea (spionid)
Polydora ciliata (spionid)
Pseudopolydora paucibranchiata (spionid)
Euchone (?) sp. (fan worm)
Sabella spallanzanii (fan worm)
Balanus improvisus (barnacle)
Megabalanus rosa (barnacle)
Megabalanus tintinnabulum (barnacle)
Notomegabalanus algicola (barnacle)
Neomysis japonica (mysid shrimp)
Tanais dulongi (tanaid)
Cirolana hardfordi (isopod)
Eurylana arcuata (isopod)
Paracerceis sculpta (isopod)
Paradella dianae (isopod)
Sphaeroma serratum (isopod)
Sphaeroma walkeri (isopod)
Synidotea laevidorsalis (isopod)
Cancer novaezelandiae (crab)
Carcinus maenas (crab)
Halicarcinus innominatus (crab)
Petrolisthes elongatus (half crab)
Pyromaia tuberculata (crab)
Palaemon macrodactylus (shrimp)
Sergiella angra (shrimp)
Maoricolpus roseus (screw shell)
Zeacumantis subcarinatus (screw shell)
Aeolidiella indica (sea slug)
Godiva quadricolor (sea slug)
Janolus hyalinus (sea slug)
Okenia plana (sea slug)
Polycera capensis (sea slug)
Polycera hedgpethi (sea slug)
Thecacera pennigera (sea slug)
Crassostrea gigas (oyster)
Ostrea lutaria (oyster)
Corbula gibba (clam)
Neilo australis (clam)
Paphirus largellierti (clam)
Musculista senhousia (mussel)
Mytilopsis sallei (striped mussel)
Perna canaliculus (mussel)
Soletellina donacoides (tellinid)
Theora lubrica (semelid)
Amaurochiton glaucus (chiton)
Anguinella palmata (bryozoan)
Bugula flabellata (bryozoan)
Conopeum tubigerum (bryozoan)
Cryptosula pallasiana (bryozoan)
Membranipora membranacea (bryozoan)
Schizoporella unicornis (bryozoan)
Watersipora arcuata (bryozoan)
Asterias amurensis (seastar)
Astrostole scabra (seastar)
Patiriella regularis (seastar)
Ascidiella aspersa (ascidian)
Ciona intestinalis (ascidian)
Molgula manhattensis (ascidian)
Styela clava (ascidian)
Styela plicata (ascidian)
Lateolabrax japonicus (sea bass)
Triso dermopterus (grouper)
Sparidentex hasta (sea bream)
Acanthogobius flavimanus (goby)
Acentrogobius pflaumi (goby)
Tridentiger trigonocephalus (goby)
Fosterygion varium (blenny)

Oncorhynchus mykiss (trout)
Oreochromis mossambicus (tilapia)
Salmo salar (salmon)
Salmo trutta (trout)
PLANTS
Alexandrium catenella (dinoflagellate)
Alexandrium minutum (dinoflagellate)
Alexandrium tamarense (dinoflagellate)
Gymnodinium catenatum (dinoflagellate)
Caulerpa taxifolia (green alga)
Codium fragile tomentosoides (green alga)
Antithamnionella spirographidis (red alga)
Arthrocladia villosa (red alga)
Polysiphonia brodiaei (red alga)
Polysiphonia pungens (red alga)
Sperococcus compressus (red alga)
Discosporangium mesarthrocarpum (brown alga)
Spacella subtilissima (brown alga)
Undaria pinnatifida (brown alga)
Zosterocarpus spp. (brown alga)

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