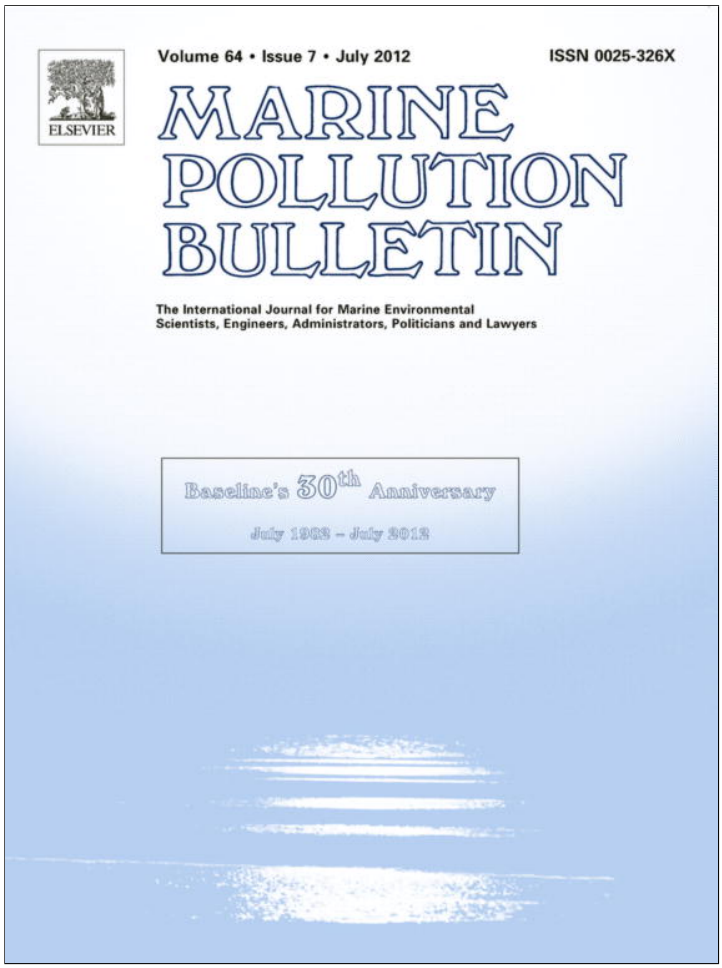

Marine Pollution Bulletin 64 (2012) 1392–1401

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Biosecurity risks associated with in-water and shore-based marine vessel hull cleaning operations

Chris M.C. Woods [a,*], Oliver Floerl [a], Liz Jones [b]

[a] National Institute of Water and Atmospheric Research Ltd., P.O. Box 8602, Riccarton, Christchurch 8011, New Zealand
[b] Ministry of Agriculture and Forestry, P.O. Box 2526, Wellington 6140, New Zealand

ARTICLE INFO

Keywords:
Biofouling
Non-indigenous species
Hull cleaning
Biosecurity
New Zealand

ABSTRACT

The removal of biofouling from vessels during hull cleaning can pose a biosecurity threat if viable, non-indigenous organisms are released into the aquatic environment. However, the effect of cleaning on biofouling organism viability in different types of cleaning operations has been poorly studied. We compared the effects of hull cleaning on biofouling organisms removed from 36 marine vessels during in-water (without capture of cleaning waste) and shore-based (with capture, and treatment of cleaning waste) cleaning. In-water cleaning resulted in higher proportions of viable biofouling organisms surviving cleaning (62.3 ± 7.1% of all organisms examined) compared to dry dock (37.8 ± 8.6%) and haul-out (20.1 ± 5.3%) operations. For shore-based facilities with effluent treatment systems, concentrations of organisms and/or their propagules in cleaning effluent was reduced by ⩾98.5% compared to initial hydro-blast effluent concentrations. These results can be used in guidance for hull cleaning operations to minimize associated biosecurity risk.

1. Introduction

The accumulation of marine growth (biofouling) on the hulls of marine vessels is an important mechanism for the introduction and spread of marine non-indigenous species among coastal locations worldwide (Minchin and Gollasch, 2003; Drake and Lodge, 2007; Davidson et al., 2008; Piola et al., 2009; Hewitt and Campbell, 2010). Biofouling development is generally prevented or mitigated through the application of 'antifouling' coatings (Schultz et al., 2011). However, antifouling coatings have a limited service life (1–5 years) and cannot be applied or provide effective protection to all parts of a vessel's hull (Piola et al., 2009). Consequently, the development of biofouling eventually occurs in-between dry-docking/haul-out cycles of most vessels (Thomason, 2010).

Development of extensive biofouling creates drag and, for engine powered vessels, reduces fuel efficiency, resulting in severe financial penalties and increased greenhouse gas emissions (WHOI, 1952; Edyvean, 2010; Schultz et al., 2011). For sailing vessels, the manoeuvrability and thus safety, of vessels can also be compromised. Most vessels of varying types are therefore regularly removed from the water for cleaning and (generally, but not always) antifouling coating renewal. Many operators also carry out in-water cleaning between successive dry-dockings/haul-outs to remove biofouling from structures whose operation or performance it may affect, such as propellers, propeller shafts, rudder shafts, sonar domes, sea chest gratings, etc. Most commercial ships are inspected out-of-water every 5 years and undergo at least one in-water inspection between dockings as part of the requirements under the Safety of Life at Sea (SOLAS) convention. The International Maritime Organisation (IMO)[1] recommends removal of biofouling at such an opportunity, but highlights the need to assess the risk to the environment of both release of organisms and release of toxic antifouling residues before proceeding.

Biofouling removed from a vessel may contain non-indigenous species. For example, Inglis et al. (2010) found that of all biofouling species identified from 508 visiting international vessels sampled at various New Zealand ports between 2004 and 2007, 68% and 5% were non-indigenous and cryptogenic species, respectively, with only 26% of those non-indigenous species known to have already established in New Zealand. Biofouling removed from vessels during cleaning therefore poses a biosecurity risk as it may contain viable, non-indigenous organisms or their reproductive propagules, and some of these may be released into the local environment during or following cleaning. The amount of biofouling waste material generated by cleaning operations can be considerable but is highly variable (e.g. McClary and Nelligan, 2001).

In New Zealand, biofouling removal and its capture, containment and disposal has historically varied widely among facilities and cleaning situations. However, most cleaning facilities now

* Corresponding author. Tel.: +64 3 3488987; fax: +64 3 3485548.
E-mail address: Chris.Woods@niwa.co.nz (C.M.C. Woods).

[1] International Maritime Organisation's Resolution MEPC.207 (62) adopted 15 July 2011 "2011 Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species".

0025-326X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2012.04.019

Table 1
Details of the five marine vessel maintenance facilities sampled in New Zealand. Cleaning and treatment methods employed by each facility for solid biofouling waste (arising from both direct hull cleaning action and as settled-out material from within effluent treatment systems) and cleaning effluent are provided for the years in which sampling occurred (2003 and 2006).

Operation	Facility	Sampling year	Cleaning method	Separation of solids and effluent	Disposal of solids	Filtration of effluent	Disposal of effluent
Dry dock	Lyttelton	2003	Hydro-blast (12,000 psi)	Settling tanks and flocculating agent	To landfill	No filtration	To sea
		2006	Hydro-blast (12,000 psi)	Settling tanks and flocculating agent	To landfill	Sand filter	To sea
Haul-out	Orams marine	2003	Hydro-blast (2500 psi)	Grit arrestors	To landfill	Sand filter	To sea
		2006	Hydro-blast (2500 psi)	Settling tanks	To landfill	Sand filter	To sewerage
	Westpark marina	2003	Hydro-blast (4000 psi)	Settling tanks	To landfill	20-mm screen	To sea
		2006	Hydro-blast (4000 psi)	Settling tanks	To landfill	20-mm screen	To sea
	Tauranga marina	2003	Hydro-blast (3500 psi)	Settling tanks	To landfill	No filtration	To sea
		2006	Hydro-blast (3500 psi)	Settling tanks	To landfill	Sand filter	To sewerage
In-water	Orams marine	2003	Hand-held scraper	n/a	To sea	n/a	n/a
		2006	Hand-held scraper	n/a	To sea	n/a	n/a
	Gulf harbour marina	2003	Hand-held scraper	n/a	To sea	n/a	n/a
		2006	Soft cloth	n/a	To sea	n/a	n/a

have controlled discharges and comply with local authority rules and consent conditions. Shore-based facilities generally now dispose of solid biofouling waste to landfill, discharge effluent to municipal sewerage systems or filtered effluent back to the sea after treatment, or recycle their treated effluent for re-use in hydro-blasting. Nevertheless, some cleaning operations (often smaller and more remote, or self-use facilities) may still discharge solid waste and/or unfiltered effluent into the sea. There has been considerable variation in the treatment and disposal methods for biofouling waste considered acceptable by various authorities (and private individuals) and the relative output/release of viable biofouling organisms (i.e. biosecurity risk) from these various methods is poorly understood.

In this paper, we describe an evaluation of the effectiveness of marine in-water and shore-based hull cleaning operations in containing and killing biofouling organisms. We compared the following cleaning operations: (1) in-water hull cleaning by divers, (2) shore-based cleaning in a commercial dry-dock, and (3) shore-based cleaning in commercial haul-out maintenance yards with varying abilities to capture and contain biofouling waste. Depending on the severity of biofouling and vessel type and size, in-water cleaning can be carried out using soft cloths, brushes or hydro-blasters, hand-held scrapers, or by diver- or remote-operated cleaning vehicles (Floerl et al., 2010). We examined the in-water removal of biofouling organisms using hand-held scrapers and soft cloths and compared it with shore-based cleaning using the common cleaning method of hydro-blasting. Whilst in-water manual cleaning using hand-held scrapers and soft cloths is not representative of large commercial operations and cleaning of larger vessels, it is nevertheless a method used by smaller vessel owners and commercial divers around the world and easily replicated, and thus we considered this the best in-water cleaning method to examine in the first instance.

2. Methods

2.1. Hull cleaning facilities

Sampling was conducted at five New Zealand hull cleaning facilities, encompassing three types of cleaning operation:

(1) Dry dock (Port of Lyttelton, Lyttelton Harbour).
(2) Haul-out (hardstand) (Orams Marine in Waitemata Harbour, Westpark Marina in the upper Waitemata Harbour and Tauranga Marina in Tauranga Harbour).
(3) In-water cleaning (Orams Marine and Gulf Harbour Marina on the Whangaroa Peninsula).

Summary details on biofouling treatment at each facility are provided in Table 1. At each facility, biofouling waste arising from hull cleaning may be subject to one, two or three successive treatment stages. Treatment stage 1 consists of the physical removal of biofouling from vessel hulls using hydro-blasting (shore-based cleaning) or hand-held scrapers/cloths/brushes (in-water cleaning). No containment of biofouling waste normally occurs in the in-water cleaning operations investigated in this study. In dry dock and haul-out facilities, solid biofouling waste is collected and disposed in landfill whilst cleaning effluent is collected in multi-chamber tanks for the settling-out of suspended solids (Treatment Stage 2). Settled waste from these is periodically removed for disposal in landfill. After cleaning effluent has passed through settlement tanks it is either discharged without filtration, or passes through a filter (Treatment Stage 3) prior to discharge to the sea or to a municipal sewerage system.

To determine the effectiveness of each treatment stage in killing biofouling organisms or preventing their re-entry into the sea, we examined the amount and viability of biofouling organisms:

(1) Prior to, and following removal of biofouling from vessel hulls (dry dock, haul-out and in-water operations).
(2) Upon entry of cleaning effluent into effluent treatment systems (dry dock and haul-out).
(3) Within effluent treatment systems (dry dock and haul-out).
(4) At discharge from effluent treatment systems (dry dock and haul-out).

We sampled a total of 36 vessels, with 18 vessels sampled during both an austral winter (2003) and summer (2006) season. Sampling at each facility included both local and non-local/international vessels. Three vessels for each facility and type of operation were sampled for each of the 2 years, giving a total of six vessels sampled for each facility and operation.

2.2. Sampling of vessel biofouling before cleaning

The amount of biofouling on each vessel was determined prior to cleaning to estimate the proportion of biofouling removed from a vessel's hull that may potentially reach the marine environment during or after cleaning, and any associated waste treatment processes. For each vessel, the "total wetted surface area (TWSA)" was determined using vessel type-appropriate equations supplied by the marine coatings industry (AkzoNobel, pers. comm.). An estimate of the proportion of TWSA covered by biofouling was obtained by determining biofouling percentage cover in 10 quadrats of 0.16 m^2 (40 × 40 cm^2) for vessels <30 m length, or 20 of these quadrats for vessels >30 m length placed at random hull locations (including main hull, rudder and keel). Total biofouling biomass (wet weight) on each vessel was estimated by the removal (hand-held scraper) and weighing of all the biofouling within each of the quadrats, and extrapolating this to the estimated TWSA covered by biofouling. Biofouling on vessel hulls is usually not distributed evenly (e.g. James and Hayden, 2000; Davidson et al., 2009). However, we used a randomised approach to obtain a broad estimate of vessel biofouling as not all areas of vessels being cleaned – particularly on larger vessels – were accessible for sampling.

2.3. Sampling of solid biofouling waste after removal from vessel hulls in shore-based facilities

After each vessel's hull was cleaned using hydro-blasters, samples of removed biofouling were collected by filling four replicate 1 L containers (where possible) with solid biofouling waste collected haphazardly from the ground below and around the vessel. For each vessel, the times of its removal from the water, duration and completion of the cleaning process, and sample collection were recorded.

Following collection of biofouling waste, each container was emptied into a sorting dish and the types of organisms, their size and state of structural damage (either completely intact or exhibiting some degree of damage) and dryness (desiccation recorded as either percentage wet/moist, semi-dry, or desiccated) recorded. Biota were separated by phylum or major taxonomic group into additional sorting dishes, covered with filtered (60 μm) seawater, and left undisturbed for 20–30 min. Biota in each sorting dish were then examined under magnification using either a handheld magnifying glass (5× magnification) or a dissecting microscope (31× magnification) for signs of active feeding and/or movement. Decisions as to whether an organism was viable ("potentially capable of living and surviving in the marine environment") were based on criteria developed with guidance from recognised taxonomic experts (Appendix A).

2.4. Sampling of hydro-blast effluent in shore-based facilities

In shore-based facilities, four replicate 10 L samples of effluent were taken at up to four separate stages in the effluent treatment process for each vessel being cleaned. Where possible, effluent was collected from: (1) hydro-blast runoff before it enters settlement tanks, (2) first chamber of the settlement tanks, (3) final chamber of the settlement tanks prior to any filtering, and (4) direct final discharge.

Effluent samples were filtered through a 60 μm sieve. The material retained from each replicate 10 L sample was sub-sampled via three replicate 2 mL samples, the contents of which were examined visually (using a dissecting micoscope) and by vital staining to determine the viability of organisms and/or propagules contained in the material. The vital stain Janus Green B was used to test for the presence of mitochondria and integrity of cellular structure (Clark, 1973).

The remaining filtrate from each replicate 10 L sample was made up to 50 mL of 5% formaldehyde/seawater and transported to a laboratory for further analysis. Three replicate subsamples (2 mL each) were taken from each 50 mL filtrate sample and any organisms and propagules within them identified and enumerated using a Leitz Fluovert FS microscope (100× magnification). The abundance of all organisms and propagules was estimated using direct counts, with the exception of filamentous algae, for which a rank scale of abundance was used due to their high numerical abundance (0–5, indicating absence (0) to very high abundance (5)).

2.5. Sampling of vessels cleaned in-water

An assessment of the viability of biofouling removed from vessel hulls during in-water cleaning operations was made at Gulf Harbour Marina and Orams Marine. Unlike shore-based operations, where cleaning activity is usually scheduled giving advance warning for sampling activity, manual in-water cleaning is not usually so well-scheduled. Hence, we opted to mimic in-water manual cleaning ourselves in a small-scale manner.

Before cleaning, the amount of biofouling on vessel hulls was determined as in Section 2.2. In-water cleaning was carried out by removing biofouling from each 0.16 m^2 quadrat using paint scrapers and soft cloths. Biofouling removed from hulls was scraped downwards into catch-bags made from fine nylon mesh (200 μm) attached to the base of the quadrats. The quantity of biofouling collected was standardised to the same volume used for vessels cleaned in shore-based facilities. Immediately after collection, all material was placed in sorting trays filled with filtered (60 μm) seawater, and organism damage, survival and viability assessed as in Section 2.3. We did not include an assessment of propagules (eggs and larvae) released from biofouling organisms during in-water cleaning, as it would not be possible to distinguish these from other sources of propagules in the water column.

2.6. Statistical analyses

Analysis of variance (ANOVA) was used to test for differences in: (1) biofouling percentage cover, (2) biofouling biomass, and (3) damage, survival and viability of organisms sampled from vessels cleaned in the various operations. No statistical analyses were carried out on viability of individual taxonomic groups due to the large variation in the number of specimens examined on different vessels in different operations. For example, the number of bryozoans and tubiculous polychaetes examined on the vessels sampled varied by a factor of 33.3 and 821.5 between cleaning operations, respectively. Statistical tests on organism viability were only performed on the combined total of all organisms of the two broad taxonomic categories of soft- and hard-bodied organisms. The linear model for this consisted of one factor, Operation (random). Because varying numbers (1–4) of replicate 1 L jars had been examined for various vessels depending on biofouling biomass, this factor was omitted from the design and individual vessels were used as the replicates in the model.

One-way ANOVA was also used to test for differences in numbers of animals, propagules and unicellular organisms in cleaning effluent among different shore-based facilities.

Data used for ANOVA were checked for normality and homogeneity of variances (Cochran's C test). Dependent variables were $\log(x+1)$ transformed if untransformed data had heterogeneous variances. However, if transformation did not remove heterogeneity of variances then untransformed data were used for the analysis (Underwood, 1997). Percentage data for analyses were arcsine square-root transformed, with weighting of 0% and 100% values ($(1/4n)$ and $[1-(1/4n)]$, respectively) (Fernandez, 1992).

3. Results

3.1. Vessels examined and their associated biofouling

The 36 vessels examined included 29 private sailing and motor yachts, four fishing vessels, two tugs, and one tanker, ranging in length from 3.4 to 104.5 m (Appendix B). There were no significant differences in percentage biofouling cover of vessels in the dry dock (mean ± s.e. = 16.0 ± 2.0%), haul-out (19.7 ± 4.0%) and in-water operations (26.3 ± 6.2%) (ANOVA, $F_{2,35} = 0.83$, $p > 0.05$), or in biofouling biomass per m^2 of vessel hulls (1.5 ± 0.4, 1.4 ± 0.5 and 0.8 ± 0.3 wet weight kg m^2, respectively) (ANOVA, $F_{2,35} = 0.45$, $p > 0.05$). However, average TWSA of vessel hulls cleaned in the dry dock (1013.3 ± 251 m^2) was greater than those in haul-out (34.6 ± 3.6 m^2) and in-water (48.9 ± 8.9) operations (ANOVA, $F_{2,35} = 75.9$, $p < 0.001$; SNK pairwise comparisons, $p < 0.05$). Consequently, total estimated vessel biofouling biomass was greater for the dry dock (321.2 ± 167 kg wet weight) than for haul-out (17.3 ± 8.9 kg) and in-water (13.1 ± 6.3 kg) operations (ANOVA, $F_{2,35} = 14.2$, $p < 0.001$; SNK pairwise comparisons, $p < 0.05$).

3.2. Solid biofouling waste

A total of 19,221 organisms were examined (Table 2). Numerically, the most abundant taxa were tubiculous polychaetes (serpulids, sabellids and spirorbids; 46.8% of organisms examined), barnacles (goose and acorn barnacles; 18.1%), bryozoans (encrusting and arborescent; 12.2%), and motile crustaceans (amphipods, isopods, and tanaids; 8.9%).

3.2.1. Desiccation and damage to biofouling organisms

Because of the relatively short period between removal of vessels from the water and the onset of cleaning in haul-out facilities, most biofouling organisms were still wet when examined. In the dry dock, the time between vessel removal from water and cleaning (11.4 ± 1.9 h) was longer than in haul-out facilities (0.4 ± 0.1 h). This longer exposure time meant that most soft-bodied organisms – especially anemones, ascidians and sponges – had become desiccated by the time cleaning commenced, whilst hard-bodied organisms such as barnacles and mussels had started to desiccate and exhibit shell-gape. However, when solid waste samples were collected, all material from haul-out and dry dock facilities was rehydrated or moist from hydro-blasting. Vessel cleaning took longer in the dry dock (41.4 ± 27.3 h) compared with haul-out facilities (0.6 ± 0.1 h) (due to larger vessel sizes.

Cleaning in the dry dock resulted in damage to a smaller proportion (75.8 ± 5.4% undamaged) of hard-bodied biofouling organisms (e.g. tubeworms and barnacles) compared to haul-out (22.9 ± 5.6%) and in-water (25.3 ± 7.1%) operations (ANOVA, $F_{2,35} = 11.6$, $p < 0.001$; SNK pairwise comparisons, $p < 0.05$; Fig. 1a). In contrast, damage to soft-bodied biofouling organisms (e.g. ascidians and sponges) was less (73.5 ± 6.2% undamaged) following in-water cleaning compared to haul-out (48.7 ± 7%) operations, but not significantly less compared to the dry dock (66.7 ± 8.8%) (ANOVA, $F_{2,35} = 4.5$, $p < 0.05$; SNK pairwise comparisons, $p < 0.05$; Fig. 1a).

3.2.2. Survival of biofouling organisms

Following cleaning, and rehydration in seawater for sample examination, the proportion of hard-bodied biofouling organisms still alive was generally low, and not significantly different among operations (ANOVA, $F_{2,35} = 2.92$, $p > 0.05$). However, the proportion of soft-bodied biofouling organisms still alive after cleaning was significantly higher (74 ± 6.7% survival) for in-water cleaning operations compared to the dry dock (34.8 ± 11.2%) and haul-out operations (28.3 ± 6.3%) (ANOVA, $F_{2,35} = 10.7$, $p < 0.001$; SNK pairwise comparisons, $p < 0.05$; Fig. 1b).

3.2.3. Viability of biofouling organisms

The percentage of surviving biofouling organisms that were deemed to be viable following cleaning varied considerably among broad taxonomic groups and cleaning operations (Fig. 1c). Viability of hard-bodied biofouling organisms was generally low in all operations, but was significantly higher for the dry dock (39.9 ± 8.6% viable) compared to haul-out (15.1 ± 4.8%) operations, but not in-water operations (23.6 ± 6.5%) (ANOVA, $F_{2,35} = 3.3$, $p < 0.05$; SNK pairwise comparisons, $p < 0.05$). Viability of soft-bodied biofouling organisms was significantly higher for in-water cleaning (71.6 ± 6.1% viable) operations compared to the dry dock (38.9 ± 10.9%) and haul-out (25.1 ± 6.5%) operations (ANOVA, $F_{2,35} = 10.8$, $p < 0.001$; SNK pairwise comparisons, $p < 0.05$; Fig. 1c).

Tubiculous polychaetes comprised 73.4% of all organisms sampled during in-water cleaning operations, but only 1.5 and 36% of those sampled in the dry dock and haul-out operations, respectively. This is likely a reflection of the fact that the in-water cleaning as carried out in this study typically involved vessels in-between dry-dockings/haul-out cycles. Therefore, these vessels should possess biofouling communities at an earlier stage of

Table 2
Number of organisms or fragments of solid biofouling material examined during sampling of 36 vessels at five marine vessel maintenance facilities in New Zealand ($n = 6$ vessels sampled at each operation/facility combination).

Taxa	Operation type/facility						Total
	Dry dock	Haul-out			In-water		
	Lyttelton dry dock	Orams marine	Westpark marina	Tauranga marina	Orams marine	Gulf harbour marina	
Algae	75	30	19	2	4	2	132
Anenomes	204	–	–	2	–	42	248
Ascidians	43	130	196	80	18	405	872
Barnacles	298	22	180	2704	11	261	3476
Bivalves	703	41	84	84	–	45	957
Bryozoans	62	923	327	210	467	355	2344
Crustaceans (motile)	1278	31	5	41	51	302	1708
Fish	–	–	–	1	–	–	1
Flatworms/nemerteans	1	–	–	–	123	2	126
Hydroids	21	11	45	132	–	1	210
Molluscs (motile)	3	–	–	1	6	7	17
Polychaetes (errant)	21	2	19	3	7	34	86
Polychaetes (tubiculous)	41	109	1116	1772	3161	2806	9005
Sponges	11	10	1	–	4	13	39
Total	2761	1309	1992	5032	3852	4275	19,221

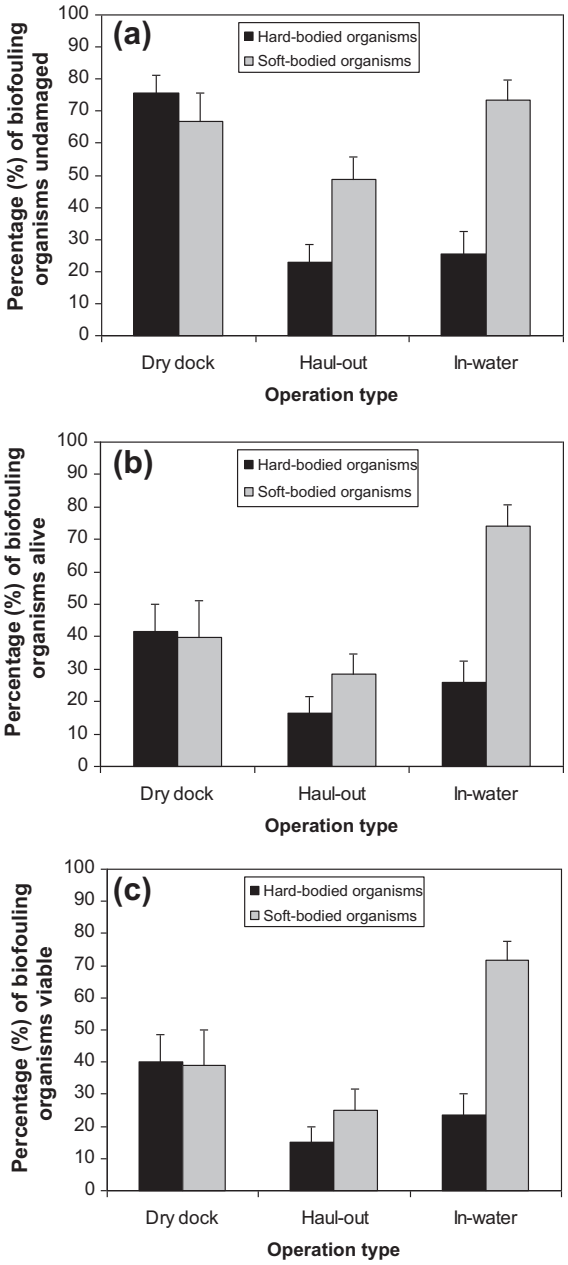

Fig. 1. Percentage (%) of hard-bodied and soft-bodied organisms undamaged (a), alive (b) and viable (c) following cleaning according to type of marine hull cleaning operation. Data are mean ± s.e.

successional biofouling community maturity (where tubiculous polychaetes are often more dominant) compared to those vessels being removed from the water for shore-based cleaning (i.e., typically undertaken at the end of the dry docking cycle). This differential proportional representation could potentially bias interpretation of sampling results. When tubiculous polychaetes were excluded from the data, the mean percentage of all organisms (hard- and soft-bodied) that were judged to be viable following in-water cleaning increased from 29.2 ± 7.2 to 62.3 ± 7.1% (Fig. 2) (Table 3). This exclusion reversed the previous pattern, indicating higher viability following in-water cleaning (62.3 ± 7.1% viable) than following cleaning in the dry dock and (37.8 ± 8.6%) and haul-out operations (20.1 ± 5.3%) (ANOVA, $F_{2,35} = 12.1$, $p < 0.001$; SNK pairwise comparisons, $p < 0.05$).

The proportion of viable organisms encountered in the various taxonomic groups examined varied considerably between operations (Table 3). Greater average percentages of ascidians, errant polychaetes, motile molluscs and sponges, and to a lesser degree bivalves and bryozoans, remained viable after in-water cleaning than after shore-based cleaning. For example, average viability of ascidians following cleaning at in-water operations was 95% compared to 42% and 38% for the dry dock and haul-out operations, respectively.

Survival and consequent viability of fragile biofouling organisms appeared to be affected most by cleaning method. Removal of biota with a scraper or soft cloth appears to be less destructive for non-brittle organisms than a hydro-blaster, with correspondingly high survival for ascidians, errant polychaetes, sponges, motile molluscs, flatworms and nemerteans following in-water cleaning. In contrast, few tubeworms survived the cleaning process in any of the operations sampled. Of the 9005 serpulids, sabellids and spirorbids that were examined in all operations, only 8.6% remained viable after cleaning, with the most common forms of damage observed in this group being fragmentation of the tube and/or the worm inside it, and/or loss of the tentacular crown and feeding structure. In nearly all cases, the only living and viable tubeworms were epibiotic on other organisms such as barnacles and bivalves. Barnacles also predominantly survived when occurring as epibionts on bivalves or when clumped together (e.g. 61–82% survival on cleaned vessels with clumped growth vs. 0–28% survival on vessels without clumped growth). Bivalves generally exhibited high mean rates of viability across all operation types, and their presence generally resulted in elevated viability of other taxa that lived on or amongst them. Most motile crustaceans (amphipods, isopods, and tanaids) examined in all cleaning operations were viable – they were generally encountered in protected micro-habitats such as empty barnacle tests, amongst bivalves or in the internal cavities of sponges that were protected from scraping and hydro-blasting. This was also the case for a range of other small soft- and hard-bodied taxa.

3.3. Cleaning effluent

3.3.1. Abundance of organisms in effluent

A total of 223 effluent samples (3.5–10 L per sample) were collected from shore-based facilities. Salinity at all stages of effluent treatment sampled was 0–0.5. Intact specimens (or identifiable fragments) of nematodes, crustaceans (mainly copepods), gastropods, bivalves, rotifers, oligotrichous ciliates, diatoms, tintinnids,

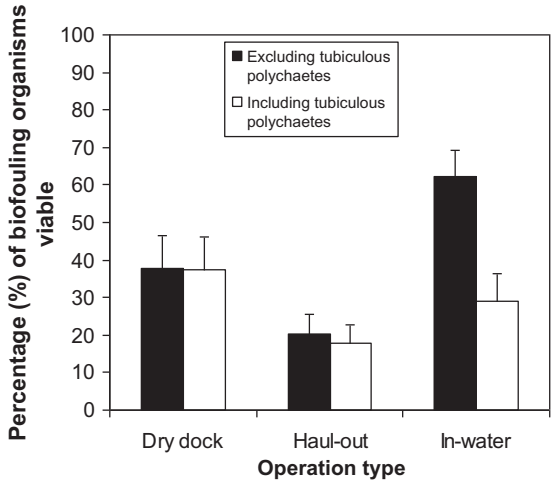

Fig. 2. Percentage (%) of viable biofouling organisms (hard- and soft-bodied combined), excluding and including tubiculous polychaetes, according to type of marine hull cleaning operation. Data are mean ± s.e.

Table 3
Percentage viability of biofouling organisms in solid biofouling waste sampled at five marine vessel maintenance facilities in New Zealand (n = 6 vessels sampled at the dry dock, 18 at haul-out, and 12 at in-water operations). Data are mean ± s.e. percent (%) viability, with total number of organisms in each taxonomic group examined included in brackets.

Taxa	Operation type		
	Dry dock	Haul-out	In-water
All organisms	37.5 ± 8.6 (2761)	17.9 ± 4.9 (8333)	29.2 ± 7.2 (8127)
All organisms (excl. tubiculous polychaetes)	37.8 ± 8.6 (2720)	20.1 ± 5.3 (5336)	62.3 ± 7.1 (2160)
Algae	71.1 ± 17.1 (75)	8 ± 4.2 (51)	66.7 ± 16.7 (6)
Anenomes	0 (204)	100 ± 0 (2)	90.5 ± 4.8 (42)
Ascidians	41.9 ± 17.1 (43)	38 ± 7.1 (406)	95.1 ± 9.4 (423)
Barnacles	33.7 ± 12.2 (298)	18.5 ± 6 (2906)	15.8 ± 6 (272)
Bivalves	52 ± 16 (703)	43.8 ± 6.9 (209)	81.7 ± 9.2 (45)
Bryozoans	34.6 ± 17.3 (62)	3.3 ± 3.1 (1460)	51.4 ± 9.5 (822)
Crustaceans (motile)	25.5 ± 20.3 (1278)	80.3 ± 8.7 (77)	87.5 ± 5.9 (353)
Fish	–	0 (1)	–
Flatworms/nemerteans	0 (1)	–	100 ± 0 (125)
Hydroids	9.2 ± 5.1 (21)	0 (188)	100 (1)
Molluscs (motile)	0 (3)	0 (1)	96 ± 2.6 (13)
Polychaetes (errant)	20 ± 9.5 (21)	33.3 ± 12.2 (24)	100 ± 0 (41)
Polychaetes (tubiculous)	12.3 ± 2 (41)	16.6 ± 7.2 (2997)	5.5 ± 2.9 (5967)
Sponges	0 (11)	14.3 ± 5.8 (11)	90.7 ± 6.5 (17)

filamentous algae, hydroids, polychaetes, foraminiferans, spores, eggs and terrestrial pollen were encountered in effluent.

Concentrations of intact animals, propagules (i.e. eggs, spores and larvae) and unicellular organisms were generally greatest in the initial effluent from hydro-blasting, ranging from total concentrations of 0–187,400/10 L. Overall, the average concentration of animals in hydro-blast runoff during cleaning was 2.3–11.7 times higher at Orams Marine (43,372 ± 10,940/10 L) and Westpark Marina (12,322 ± 5598) than at the Lyttelton dry dock (3790 ± 938) or the Tauranga Marina (5301 ± 1923) (ANOVA, $F_{3,78} = 7.05$ $p \leqslant 0.001$, SNK pairwise comparisons $p < 0.05$). Hydro-blast runoff at Orams Marine and the Lyttelton dry dock had a higher concentration of unicellular organisms (1752 ± 527 and 4318 ± 1541/10 L, respectively) than that at the other facilities (approx. 500/10 L) (ANOVA, $F_{3,78} = 6.08$, $p < 0.001$, SNK pairwise comparisons $p < 0.05$). Concentrations of propagules in hydro-blast runoff did not significantly vary between facilities and ranged from 0 to 1876 propagules/10 L (ANOVA, $F_{3,78} = 1.77$, $p > 0.05$).

Across all facilities, settlement and filtration progressively reduced the mean concentrations of organisms entrained in the effluent. In samples taken from the first chamber of the multi-chamber settlement tanks, concentrations of animals, propagules and unicellular organisms were reduced by between 20.5% and 100%, and the rank abundance of filamentous algae decreased by a range of 10–80% (Table 4). Concentrations of animals, propagules and unicellular organisms in samples taken from the final settlement chamber had been reduced by a range of 75.6–100% and abundance of filamentous algae by 100% (where able to be sampled). Where samples were taken of final effluent, concentrations of animals, propagules and unicellular organisms had been reduced by $\geqslant$98.5% compared with concentrations observed in the hydro-blast runoff, while abundance of filamentous algae had been reduced by a range of 61.5–100% (Table 4). In terms of actual abundances of animals, propagules and unicellular organisms being discharged (either back to the sea or sewerage) in the final effluent, this equated to mean abundances of 0–98.5 ± 54.3, 0–5.2 ± 3.2 and 0–17.9 ± 7.5/10 L exiting facility effluent systems, respectively. Material encountered in the final effluent included nematodes, copepods, polychaetes, rotifers, ciliates, diatoms, dinoflagellates, tintinnids, filamentous algae, propagules/zoospores and detrital aggregations, and ranged in size from 50 to 500 μm.

3.3.2. Viability of organisms in effluent

During winter sampling, positive mitochondrial stains were obtained in samples from the first settlement tank chamber of the Lyttelton dry dock and the Tauranga Marina. During summer, positive mitochondrial stains were obtained from the first and final settlement tank chambers in all facilities, and from the final effluent at the Lyttelton dry dock and the Tauranga Marina. However, only in filamentous algae was the stain clearly retained within intact cell walls. For most other biota, staining was observed within fragments of organisms. Complete exoskeletons of crustaceans and bryozoans (and other taxa) were in most cases found to be empty and did not stain properly. In all effluent samples, visible movement of organisms (mainly nematodes) was observed only in the initial hydro-blast effluent from three vessels sampled during winter and four vessels sampled during summer. No movement of organisms was observed at any other stage of treatment.

4. Discussion

Along with ballast water discharge, hull cleaning activities offer a direct pathway for introducing viable non-indigenous organisms associated with marine vessels into new environments. Biofouling waste generated during marine vessel maintenance activities that is not effectively captured/contained/killed poses a biosecurity risk if the waste contains viable non-indigenous organisms and/or their propagules, and is discharged back into the marine environment. However, the extent to which hull cleaning activities contribute to successful introductions of non-indigenous biofouling organisms is currently unknown. Because it is not common practice for vessel owners/companies to determine whether the biofouling on their vessels contains non-indigenous organisms prior to hull cleaning, a precautionary approach could be adopted assuming that all biofouling removed during cleaning activities may contain non-indigenous species. It is thus desirable to ensure that hull cleaning operations should be undertaken in a way that contains and, ideally, kills all biofouling organisms removed from hull surfaces (Takata et al., 2006; Roberts and Tsamenyi, 2008; Floerl et al., 2010).

Whilst it is commonly accepted that 'traditional' manual in-water cleaning without specialised containment systems can be associated with the release of a wide variety of viable biofouling organisms and their propagules into the marine environment, more so than shore-based operations, this study helps to quantify the post-cleaning viability rates of biofouling organisms associated with this type of operation. A mean percentage of ~62% of all organisms in solid waste were judged to be viable following in-water cleaning using hand-held scrapers/soft cloths. However,

Table 4
Abundance of animals, propagules, unicellular organisms and filamentous macroalgae at various stages of effluent treatment at four shore-based marine vessel maintenance facilities sampled in New Zealand. Data are mean ± s.e. numbers of organisms, except for filamentous algae where a rank scale of abundance was used due to their high numerical abundance (0–5, indicating absence (0) to very high abundance (5)). Percentage (%) values in brackets represent abundance reduction relative to the concentrations observed in initial hydro-blast effluent. Austral winter sampling was conducted in 2003 and austral summer sampling in 2006. Where sampling of effluent was not possible due to accessibility restrictions this is indicated by (–). * = Accidental stirring-up of tank sediments in the final settlement tank during sampling precluded accurate assessment of sample contents at the final settlement tank and final discharge stages at Westpark Marina in Summer 2006.

	Lyttelton dry dock		Orams marine		Westpark marina		Tauranga marina	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Animals								
Hydro-blast effluent	6193.6 ± 2097.9	2188 ± 134	36,648.5 ± 6195.8	47,855 ± 36,936	1317.8 ± 381.7	16,004 ± 13,307	9641.0 ± 3254.3	595 ± 281
1st tank	783.6 ± 748.9 (87.4%)	175 ± 105 (92%)	10.0 ± 10.0 (99.9%)	19,576 ± 9782 (59.1%)	142.8 ± 98.3 (89.2%)	69 ± 0 (99.6%)	5583.1 ± 1631.9 (42.1%)	5.2 ± 1.8 (99.1%)
Final tank	–	1.7 ± 0.9 (99.9%)	–	11.8 ± 3.4 (99.9%)	-	*	–	1.7 ± 1.3 (99.7%)
Final discharge	1.8 ± 1.8 (99.7%)	13 ± 1.7 (99.4%)	0 (100%)	–	–	*	98.5 ± 54.3 (99%)	0.7 ± 0.7 (99.9%)
Propagules								
Hydro-blast effluent	553.7 ± 198.7	39 ± 12	72.2 ± 47.4	87.1 ± 85.6	134.9 ± 88.5	135.6 ± 73.4	834.4 ± 327.8	12.7 ± 10.1
1st tank	333.9 ± 224.6 (39.7%)	7.9 ± 6.9 (79.7%)	11.2 ± 11.2 (84.5%)	16.7 ± 8.3 (80.9%)	31.7 ± 6.3 (76.5%)	5.7 ± 0 (95.8%)	421.2 ± 161.2 (49.5%)	10.1 ± 7.5 (20.5%)
Final tank	–	5.2 ± 4.2 (86.7%)	–	0 (100%)	0 (100%)	*	–	3.1 ± 2.6 (75.6%)
Final discharge	5.2 ± 3.2 (99.1%)	0.6 ± 0.6 (98.5%)	0 (100%)	–	–	*	0 (100%)	0 (100%)
Unicellular org.								
Hydro-blast effluent	1905.6 ± 474.9	5926 ± 4246	1848.9 ± 250.2	1689 ± 1647	1827.5 ± 414.7	67 ± 41	2878.9 ± 1425.2	0.5 ± 0.5
1st tank	20.5 ± 11.7 (98.9%)	696 ± 435 (88.3%)	0 (100%)	68 ± 32 (96%)	63.6 ± 25.3 (96.5%)	5.2 ± 0 (92.2%)	1143.9 ± 428.7 (60.3%)	0.3 ± 0.3 (40%)
Final tank	–	10.4 ± 7.7 (99.8%)	–	0.7 ± 0.3 (99.9%)	–	*	–	0 (100%)
Final discharge	0 (100%)	5.7 ± 2.1 (99.9%)	0 (100%)	–	–	*	17.9 ± 7.5 (99.4%)	0 (100%)
Filament. Algae								
Hydro-blast effluent	5 ± 0	0	5 ± 0	0.4 ± 0.4	5 ± 0	0.8 ± 0.8	3.9 ± 0.2	0.8 ± 0.8
1st tank	1 ± 0 (80%)	n/a	1 ± 0 (80%)	0.3 ± 0.3 (25%)	4.5 ± 0.6 (10%)	0.5 ± 0.5 (37.5%)	3 ± 1.3 (23.1%)	0.5 ± 0.5 (37.5%)
Final tank	-	n/a	–	0 (100%)	–	*	–	0 (100%)
Final discharge	1 ± 0 (80%)	n/a	0.8 ± 0.3 (84%)	–	–	*	1.5 ± 0.6 (61.5%)	0 (100%)

biofouling waste in shore-based operations can also contain significant amounts of viable material. Overall, across all types of shore-based operations examined, a mean percentage of ~23% of all organisms were judged to be viable following cleaning. This highlights the importance of preventing direct release of solid and liquid cleaning waste back into the marine environment from shore-based operations (e.g. sweeping solid waste and discharging untreated hydro-blast effluent into the sea). There is also some biosecurity risk associated with shore-based cleaning via escape of mobile biofouling organisms before cleaning operations commence. For example, Coutts et al. (2010) demonstrated the potential escape-risk of mobile biofouling organisms from vessels being removed from the sea for shore-based cleaning through a mimic experiment using pre-fouled settlement plates. They found that settlement plates with varying degrees of biofouling development lost 3.2–19.8% of total biofouling animals (e.g., errant polychaetes, amphipods, crabs, tanaids and fishes) for emersion exposures of just 0.5–15 min. This further highlights the need for shore-based cleaning facilities to employ practices/infrastructure that maximise the capture and retention of vessel biofouling.

4.1. Shore-based hull cleaning

Waste generated during hull cleaning using abrasive tools or hydro-blasting can contain small fragments of antifouling coating along with removed biofouling (Turner, 2010). Because of the contamination risks posed by such particles, New Zealand and Australia have developed guidelines (i.e. the Australia and New Zealand Environment and Conservation Council (ANZECC) Code of Practice for Antifouling, In-Water Hull Cleaning and Maintenance; ANZECC, 1997) and legislation (e.g. New Zealand's Resource Management Act 1991, http://www.mfe.govt.nz/rma/index.html) that require commercial cleaning facilities to have adequate capture and treatment systems (Floerl et al., 2010). In New Zealand, not all shore-based vessel cleaning facilities possess adequate means for preventing the discharge of viable organisms or propagules into the marine environment, particularly via effluent, and the expectations of environmental management authorities vary regionally (McClary and Nelligan, 2001; Floerl et al., 2005). Some self-use facilities around New Zealand are still located in tidal areas, where biofouling and antifouling coating waste may re-enter the marine environment with the incoming tide (Woods and Floerl, pers. obs.). Our results highlight the importance of equipping new, or retrofitting existing facilities, with systems that are capable of retaining viable biological material.

It is important to ensure that a complementary approach is taken between setting biosecurity regulations and ensuring that appropriate treatment options are available to facilitate those regulations. In New Zealand, this message is being strengthened through the government's Marine Behaviour Change Programme (MAF Biosecurity New Zealand, 2008) that provides guidance for hull maintenance, and in the Facility Standards (MAF Biosecurity New Zealand, 2011) for facilities to be used for cleaning arriving vessels that are non-compliant with the vessel Import Health Standard (IHS) under development. The IHS and its associated guidance document is to be released in April 2012, giving requirements for vessels arriving to New Zealand to arrive with a clean hull (but includes some allowance of early stage biofouling and thresholds for acceptable biofouling will vary for vessels arriving for a short- or long-term), or take measures to achieve the same reduction in biosecurity risk from the biofouling pathway through acceptable biofouling management plans. This IHS will be voluntary for the first 4 years (until 2016) while vessels become compliant by improving their biofouling management regimes (where needed). The Facility Standards will allow for hull cleaning to be conducted on grassy areas away from the sea, with no collection of waste and discharge onto the grass, in unusual circumstances where visiting yachts requiring biofouling removal arrive at a port that is not equipped for such activity. It is likely that vessel cleaning facilities lacking adequate capturing and filtration systems exist in many locations globally and, as such our findings should be relevant for the design and management of international vessel cleaning facilities.

We found that where effluent treatment systems are in place at shore-based facilities, they are highly effective at reducing the abundance of viable organisms or propagules in the final discharged effluent. On average, the facilities we examined removed ~99% of the organisms and propagules contained in the initial cleaning runoff. This equated to mean abundances of 0–98.5 ± 54.3, 0–5.2 ± 3.2 and 0–17.9 ± 7.5/10 L for animals, propagules and unicellular organisms (respectively) entrained within cleaning effluent exiting facility effluent systems. Whilst the substantial reductions in biological material exiting the cleaning facilities examined compared to those found in the initial hydro-blast effluent are encouraging and demonstrate the benefit of effluent treatment systems, they also show that there may still be a biosecurity risk if those entrained organisms remain viable and are discharged directly back to the sea. (Our data suggested that the vast majority of biological material exiting the facilities examined in this study was unlikely to be viable.). The observed reduction in abundance was achieved via a series of freshwater settlement chambers and filters. The effectiveness of settlement chambers (i.e. particle settlement/capture and/or freshwater-induced mortality) is affected by the residence time of the effluent pumped through them, which in turn is affected by the frequency of cleaning events at each facility in conjunction with effluent treatment system design (e.g. number, design and capacity of settlement tanks, as well as use of flocculating or precipitating agents) and nature of the vessels being cleaned. New facilities or those planning to retrofit settlement and filtration systems should ensure that their effluent treatment systems are appropriate to the frequency of cleaning events expected, type of vessels to be cleaned and can adequately capture and process the commensurate volumes of solid and liquid waste generated.

McClary and Nelligan (2001) recommended the capture of particles above an average size threshold of 60 μm diameter before discharge back to the marine environment. This was deemed as an acceptable level of security to contain the adult and propagule stages of 43 biofouling target species considered first-order risks of introduction into New Zealand (at the time). Oemcke (1999) suggested that filtration to a size of 20 μm should remove the hypnocysts of toxic dinoflagellate algae that can be carried within silt contained within the biofouling matrix on vessel hulls (Minchin et al., 2006). If elimination of smaller vessel-borne organisms such as viruses (55–200 nm), bacteria (0.2–5 μm) and some protozoa (2–100 μm) ever becomes a biosecurity objective, then physical disinfection treatment options include ultraviolet (UV) irradiation, high power ultrasound and possibly ozonation (Oemcke, 1999). Alternatively, rather than apply fine-screening and any of the other above further treatment of discharge effluent, it would seem logical either not to discharge treated effluent back into the marine environment, for example by discharging it to a municipal sewerage system. Non-discharge of treated effluent could also be facilitated by the storage and recycling of treated effluent as the water source for the hydro-blasters. This latter practice is gaining favour in New Zealand not only as a compliance mechanism for meeting relevant Regulatory Authorities requirements, but also as a freshwater conservation measure.

4.2. In-water hull cleaning

In-water cleaning of vessel hulls is widely used around the world (Bohlander, 2009; Floerl et al., 2010). It is practiced by up

to 66% of yacht owners around New Zealand and Australia (Floerl et al., 2005, 2008) because it is simple, cheap (or even free if vessel owners conduct it themselves) and because it may delay costly antifouling coating renewals. For example, Floerl et al. (2010) estimated in-water manual cleaning using commercial divers on a standard 12-m sailing yacht to cost~AU$240 in Australia compared with AU$575 for haul-out and hydro-blasting onshore. For larger commercial vessels, in-water cleaning may also be significantly cheaper than cleaning in dry-docks or haul-out facilities, and possibly have greater availability. Floerl et al. (2010) found that in Australia the approximate cost of in-water removal of biofouling from all hull and niche areas varied from AU$10,500–27,000 (50-m vessel, plus 1–2 days of lost revenue)–AU$65,000–92,000 (200-m vessels, plus 3–5 days lost revenue). In contrast, dry-docking and biofouling removal from hull and niche areas (including sea chests) was associated with a cost of AU$26,000 (vessels up to 50 m in length) to AU$195,000 (ships over 200 m), plus 1–3 days of lost revenue (excluding any consequent antifoulant coating renewal cost and time) (Floerl et al., 2010).

The current ANZECC Code of Practice (ANZECC, 1997) strongly discourages in-water cleaning in New Zealand and Australia due to the associated contamination and biosecurity risks. However, since the release of this Code of Practice, three significant developments have occurred: (1) antifouling coatings containing the organotin compound tributyltin (TBT) have been banned (International Maritime Organisation (IMO), 2002), (2) new coating technologies have been developed, including non-biocidal systems that require regular grooming and cleaning (e.g. Chambers et al., 2006; Almeida et al., 2007), and (3) there has been a change of attitude toward in-water cleaning, and the concomitant recognition that, if done 'properly', it may provide biosecurity benefits in certain situations. This is illustrated by the current redrafting of the ANZECC Code of Practice (1997) (DAFF, 2011; MAF, 2011) and the endorsement of certain types of in-water cleaning practices by the IMO (IMO, 2011). The redrafting of the ANZECC Code of Practice recognises the ability for approving authorities to assess biosecurity risk on a case-by-case basis conditional on the biofouling level, whether the NIS present on the hull are already established in the immediate area, and the containment or killing technology that is proposed to be used during hull cleaning. The recent IMO guidelines accept in-water hull cleaning as a regular maintenance tool to remove marine 'slime' (microfouling) and prevent the establishment of mature and extensive biofouling assemblages (macrofouling) on vessel hulls. Both initiatives emphasise the need to use cleaning technologies that are appropriate to the type of antifouling coating(s) used on a vessel and that prevent the release of unacceptable quantities of biofouling or coating material into the surrounding environment.

Unfortunately, such technologies are currently not widely commercially available (see reviews by Bohlander, 2009 and Floerl et al., 2010). Pilot versions of capture and containment technologies for in-water hull cleaning have been developed and subjected to small-scale trials (e.g. Coutts, 2002; Hopkins et al., 2008), but at this stage are not fully effective. However, it is likely that the provision of regulatory and commercial incentives will result in the development and testing of effective cleaning and containment technology in the near future.

4.3. Conclusion

In this study, we have quantified that manual in-water hull cleaning with no capture and treatment of removed biofouling organisms represents a greater biosecurity risk (if non-indigenous organisms are present) than shore-based hull cleaning, where capture and treatment of biofouling waste generated during cleaning typically occurs. The former type of cleaning operation results in a higher proportion of biofouling organisms remaining viable after cleaning, and these are released directly back into the marine environment, in comparison to shore-based operations which produce lower viability rates as well as capturing and killing the vast majority of organisms removed from vessels. For shore-based hull cleaning, the exposure to freshwater and associated mechanical damage during hull cleaning, the use of settlement tanks for organism/particle collection, and physical screening are valuable tools for reducing biofouling viability and increasing its retention, but each does not stand alone as an effective treatment option. Complete collection and proper disposal of all biofouling material through sequential treatment techniques is required to remove biosecurity risks associated with shore-based cleaning.

The extent and origin of biofouling on a vessel influence whether the use of in-water cleaning is advisable or even sensible (Floerl et al., 2010). For example, the presence of extensive biofouling on biocidal antifouling coatings likely indicates that coating failure has occurred and that renewal is required. In such situations, in-water cleaning would only provide a short-term benefit for the vessel's operation. Nevertheless, in-water cleaning can be a sensible management or maintenance tool in other situations. However, until in-water cleaning options are available that achieve effective capture and containment of biofouling waste, shore-based cleaning of vessels that may harbour non-indigenous species is the best option to reduce biosecurity risk (if this option is available) (Hopkins et al., 2008; Floerl et al., 2010).

The New Zealand Government is considering actions to minimise biosecurity risks associated with international vessel arrivals. This has resulted in the release of a draft Import Health Standard (aligning with IMO biofouling guidelines: IMO 2011) that requires vessels to achieve a specified level of hull hygiene upon entering the country (MAF Biosecurity New Zealand, 2010). The introduction of such standards – in New Zealand or elsewhere – will provide valuable biosecurity benefits, but will also require that complementary adequate treatment solutions are available for non-compliant vessels. In New Zealand, this message is being strengthened through both the government's Marine Behaviour Change Programme that provides guidance for hull maintenance, and in the IHS and its associated guidance document to be released in April 2012. As stated earlier, this IHS will be voluntary for 4 years (unless biosecurity inspectors detect biofouling that is likely to cause serious adverse impact on New Zealand resources) while vessels become compliant by improving their biofouling management regimes (where needed), and possibly while facilities and in-water options become established for treatment of arriving vessels that are non-compliant and wish to stay in New Zealand. However, shore-based cleaning facilities are generally limited and often associated with long waiting times, especially for larger vessels. This further emphasises preventative biofouling management and the need for developing and commercialising effective and environmentally safe tools for in-water biofouling removal.

Acknowledgments

We thank the following cleaning facility staff for their assistance: Hal Upton (Lyttelton dry dock), Craig Park (Orams Marine Maintenance), Kevin Lidgard (Westpark Marina), Bob Ellis and Andrew (Tauranga Marina Society), and Tom Warren (Gulf Harbour Marina). We gratefully acknowledge the assistance of Isla Fitridge, Olivia Johnston, Karen Robinson, David Rupp, Niki Davey, Nicola Rush, Matt Smith of NIWA during fieldwork and laboratory analyses. We also thank Don Morrisey (NIWA), Jennie Brunton (MAF) and an anonymous reviewer for their reviews of an earlier draft of the manuscript. Funding was provided by MAF Biosecurity New Zealand (Projects ZBS2002-04 and ZBS2005-22).

Appendix A. and B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2012.04.019.

References

Almeida, E., Diamantino, T.C., de Sousa, O., 2007. Marine paints: the particular case of antifouling paints. Progress in Organic Coatings 59 (1), 2–20.

ANZECC, 1997. Code of practice for antifouling and in-water cleaning and maintenance. Prepared by the Australian and New Zealand Environment and Conservation Council (Maritime Accidents and Pollution Implementation Group), Canberra, Australia. <http://www.environment.gov.au/coasts/pollution/antifouling/code/pubs/code.pdf> (access date December 2011).

Bohlander, J., 2009. Review of options for in-water cleaning of ships. MAF biosecurity New Zealand Technical Paper No. 2009/42. <http://www.biosecurity.govt.nz/files/pests/salt-freshwater/options-for-in-water-cleaning-of-ships.pdf> (access date December 2011).

Chambers, L.D., Stokes, K.R., Walsh, F.C., Wood, R.J.K., 2006. Modern approaches to marine antifouling coatings. Surface and Coatings Technology 201, 3642–3652.

Clark, C., 1973. Staining Procedures. Williams and Wilkins, Baltimore, USA.

Coutts, A.D.M., 2002. The development of incursion response tools – underwater vacuum and filter system trials. Cawthron Report No. 755, Cawthron Institute, Nelson, New Zealand.

Coutts, A.D.M., Valentine, J.P., Edgar, G.J., Davey, A., Burgess-Wilson, B., 2010. Removing vessels from the water for biofouling treatment has the potential to introduce mobile non-indigenous marine species. Marine Pollution Bulletin 60, 1533–1540.

DAFF, 2011. Draft antifouling and in-water cleaning guidelines. <http://www.daff.gov.au/animal-plant-health/pests-diseases-weeds/marine-pests/draft-antifouling-and-inwater-cleaning-guidelines> (access date December 2011).

Davidson, I.C., McCann, L.D., Sytsma, M.D., Ruiz, G.M., 2008. Interrupting a multi-species bioinvasion vector: the efficacy of in-water cleaning for removing biofouling on obsolete vessels. Marine Pollution Bulletin 56 (9), 1538–1544.

Davidson, I.C., Brown, C.W., Sytsma, M.D., Ruiz, G.M., 2009. The role of containerships as transfer mechanisms of marine biofouling species. Biofouling 25 (7), 645–655.

Drake, J.M., Lodge, D.M., 2007. Hull fouling is a risk factor for intercontinental species exchange in aquatic ecosystems. Aquatic Invasions 2 (2), 121–131.

Edyvean, R., 2010. Consequences of fouling on shipping. In: Thomason, J.C., Durr, S. (Eds.), Biofouling. Wiley-Blackwell, Oxford, UK, pp. 217–225.

Fernandez, G.C.J., 1992. Residual analysis and data transformations: important tools in statistical analysis. HortScience 27 (4), 297–300.

Floerl, O., Inglis, G.J., Marsh, H.M., 2005. Selectivity in vector management: an investigation of the effectiveness of measures used to prevent transport of non-indigenous species. Biological Invasions 7, 459–475.

Floerl, O., Smith, M., Inglis, G., Davey, N., Seaward, K., Johnston, O., Fitridge, I., Rush, N., Middleton, C., Coutts, A., 2008. Vessel biofouling as a vector for the introduction of non-indigenous marine species to New Zealand: Recreational yachts. NIWA Client Report prepared for MAF Biosecurity New Zealand, Research Project ZBS2004-03A.

Floerl, O., Peacock, L., Seaward, K., Inglis, G., 2010. Review of biosecurity and contaminant risks associated with in-water cleaning. NIWA client report commissioned by the department of agriculture, fisheries and forestry (DAFF). <http://www.marinepests.gov.au/__data/assets/pdf_file/0005/1804478/Review_of_biosecurity_and_contaminant_risks_associated_with_in-water_cleaning.pdf> (access date December 2011).

Hewitt, C., Campbell, M., 2010. The relative contribution of vectors to the introduction and translocation of marine invasive species. The national centre for marine conservation and resource sustainability within the Australian maritime college client report commissioned by the department of agriculture, fisheries and forestry (DAFF). <http://www.marinepests.gov.au/__data/assets/pdf_file/0004/1804513/Relative_contribution_of_vectors_to_the_introduction_and_ translocation_of_invasive_marine_species.pdf> (access date December 2011).

Hopkins, G., Forrest, B., Coutts, A., 2008. Determining the efficacy of incursion response tools: rotating brush technology (coupled with suction capability). MAF Biosecurity New Zealand Technical Report: 2009/39. <http://www.biosecurity.govt.nz/files/pests/salt-freshwater/marine-response-tools-rotating-brushes.pdf> (access date December 2011).

International Maritime Organization, 2002. Anti-fouling systems. <http://www.imo.org/OurWork/Environment/Anti-foulingSystems/Documents/FOULING2003.pdf> (access date December 2011).

International Maritime Organization, 2011. Guidelines for the control and management of ships' biofouling to minimise the transfer of invasive aquatic species. MEPC 62/24/Add.1, Annex 26. <http://www.imo.org/blast/blastDataHelper.asp?data_id=30766&filename=207(66).pdf> (access date December 2011).

Inglis, G.J., Floerl, O., Ahyong, S.T., Cox, S.L., Unwin, M., Ponder-Sutton, A., Seaward, K., Kospartov, M., Read, G., Gordon, D., Hosie, A., Nelson, W., D'Archino, R., Bell, A., Kluza, D., 2010. The Biosecurity Risks Associated with Biofouling on International Vessels Arriving in New Zealand: Summary of the patterns and predictors of fouling. NIWA Client Report prepared for MAF Biosecurity New Zealand Policy and Risk Directorate, Research Project RFP0811321.

James, P., Hayden, B., 2000. The potential for the introduction of exotic species by vessel hull fouling: a preliminary study. NIWA Client, Report No. WLG00/51.

MAF, 2011. Draft antifouling and in-water cleaning guidelines <http://www.maf.govt.nz/news-resources/consultations/draft-antifouling-and-in-water-cleaning-guidelines.> (access date December 2011).

MAF Biosecurity New Zealand, 2008. Marine behaviour change programme. <http://www.biosecurity.govt.nz/biosec/camp-acts/marine> (access date December 2012).

MAF Biosecurity New Zealand, 2010. Draft import health standard for vessel biofouling. <http://www.biosecurity.govt.nz/files/biosec/consult/draft-bnz-std-biofoul.pdf> (access date December 2011).

MAF Biosecurity New Zealand, 2011. Standard for general transitional facilities for uncleared goods (TF Gen). <http://www.biosecurity.govt.nz/border/transitional-facilities/bnz-std-tfgen> (access date December 2011).

McClary, D.J., Nelligan, R.J., 2001. Alternate biosecurity management tools for vector threats: technical guidelines for acceptable hull cleaning facilities. Kingett Mitchell & Associates Ltd. Report prepared for the New Zealand Ministry of Fisheries (Project ZBS2000/03). <http://www.biosecurity.govt.nz/files/pests/salt-freshwater/kma-hull-cleaning-guidelines.pdf> (access date December 2011).

Minchin, D., Gollasch, S., 2003. Fouling and ships' hulls: how changing circumstances and spawning events may result in the spread of exotic species. Biofouling 19 (Supplement), 111–122.

Minchin, D., Floerl, O., Savini, D., Occhipinti-Ambrogi, A., 2006. Small craft and the spread of exotic organism. In: Davenport, J., Davenport, J.L. (Eds.), The Ecology of Transportation: Managing Mobility for the Environment. Springer, The Netherlands, pp. 99–118.

Oemcke, D., 1999. The treatment of ships' ballast water. EcoPorts Monograph Series No. 18, Ports Corporation of Queensland, Brisbane, Australia.

Piola, R.F., Dafforn, K.A., Johnston, E.L., 2009. The influence of antifouling practices on marine invasions. Biofouling 25, 633–644.

Roberts, J., Tsamenyi, M., 2008. International legal options for the control of biofouling on international vessels. Marine Policy 32, 559–569.

Schultz, M.P., Bendick, J.A., Holm, E.R., Hertel, W.M., 2011. Economic impact of biofouling on a naval surface ship. Biofouling 27, 87–98.

Takata, L., Falkner, M., Gilmore, S., 2006. Commercial vessel fouling in California: analysis, evaluation, and recommendations to reduce nonindigenous species release from the non-ballast water vector. California State Lands Commission, Marine Facilities Division, USA.

Thomason, J.C., 2010. Fouling on shipping: data-mining the world's largest antifouling archive. In: Thomason, J.C., Durr, S. (Eds.), Biofouling. Wiley-Blackwell, Oxford, UK, pp. 207–216.

Turner, A., 2010. Marine pollution from antifouling paint particles. Marine Pollution Bulletin 60, 159–171.

Underwood, A.J., 1997. Experiments in Ecology: Their Design and Interpretation Using Analysis of Variance. Cambridge University Press, UK.

Woods Hole Oceanographic Institution (WHOI), 1952. Marine fouling and its prevention. Contribution No. 580. United States Naval Institute, Annapolis, MD, USA.