Hull Fouling of Maritime Vessels as a Pathway for Marine Species Invasions to the Hawaiian Islands

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Abstract
The natural barriers to species invasions that exist in isolated marine environments such as Hawaii are overcome by anthropogenic influences on the dispersal patterns of marine organisms. This creates a situation where the marine habitats of the Hawaiian Archipelago are more readily exposed to nonindigenous species. A case study of a particular anthropogenic dispersal mode, maritime vessel hull fouling, is reviewed. This mode has effects on human altered habitats such as Honolulu Harbor and Pearl Harbor.

INTRODUCTION

The native species of the marine and terrestrial environments of Hawaii arrived as natural biological invasions through historical time, and through evolution and adaptation became the present communities associated with the archipelago. The Hawaiian Islands are one of the most isolated areas in the world and all native plants and animals exist due to the pioneering species that settled here originally. The advent of modern history has created new human – mediated, or anthropogenic, biological invasions of non-indigenous species (NIS) through non-natural mechanisms. Hawaii is of special concern with respect to NIS introductions (marine and terrestrial) because tropical, insular systems may be more susceptible to invasion than continental systems (Vitousek et al. 1987).

Biological invasions brought about by anthropogenic influences have occurred throughout the world through a variety of mechanisms including maritime shipping, live seafood and bait shipments, aquaculture, shipments of commercial and institutional aquarium species, and the activities of education and research institutions. The primary pathway identified for marine NIS introductions has been maritime vessel traffic to ports around the world through ballast water discharge (Williams et al. 1988; Carlton & Geller 1993; Ruiz et al. 2000). Although this pathway is blamed for the majority of marine NIS introductions around the United States, the amount of ballast water being released varies among ports (Carlton et al. 1995; Smith et al. 1996, Godwin and Eldredge 2001). There are other pathways associated with maritime vessel activity that can be responsible for introductions.

Maritime vessel activity acting as a vector for marine NIS is a complex issue involving more than just ballast water. Ocean-going vessels can be thought of as biological islands for species that dwell in harbors and estuaries around the world. These vessels provide substrate for the settlement of species associated with fouling communities, protected recesses that can be occupied by both sessile and mobile fauna, and enclosed spaces that hold water in which everything from plankton to fish can become entrained (Wonham et al. 2000). The pathways associated with and ocean-going vessel are ballast water, ballast water sediments, and hull fouling. This paper will focus on hull fouling as a pathway of great importance for the introduction of marine NIS to Hawaii. The information in this paper is based on findings of the South Oahu Marine Invasions Shipping Study (SOMISS Godwin and Eldredge 2001), which was conducted from March 1998 through December 1999. The focus of SOMISS was to broadly survey the commercial maritime shipping industry as a source for marine NIS introductions to Hawaii through the examination of ballast water, ballast water sediments, and hull fouling communities.

MARINE NON-INDIGENOUS SPECIES INVASIONS

Marine habitats can be considered robust when dealing with disturbances such as climate change and glaciation measured over millions of years. When disturbances are more intense over shorter time scales, the marine environment can be considered to be fragile. It is these short time frames and intense disturbances that are relevant to human society and the anthropogenic effects induced on marine habitats. The introduction of marine NIS can cause irreversible alterations to marine communities and is an anthropogenic disturbance that has become of great concern.

In the terrestrial environment the issue of NIS invasion and control has been dealt with as a management issue for some time. The concept of marine NIS is a relatively new issue, in comparison (Office of Technology Assessment 1993; NRC 1996). In the United

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States, awareness of marine NIS in the federal government and the scientific community has increased more since the late 1980's than in the past 30 years (Carlton 1993). This can be attributed to the invasion of the Eurasian Zebra Mussel *Dreissena polymorpha*, which was first collected in the Great Lakes in 1988 (Nalepa and Schloesser 1993). The Zebra Mussel has overwhelmed the benthic communities of the Great Lakes but the economic impacts and not the ecological ramifications are what brought it to the attention of public officials. The Zebra Mussel is a prolific fouling organism in its new environment - the Great Lakes - and one of the consequences is the clogging of cooling intakes of power plants. The cost of control of the Zebra Mussel was expected to reach US$500 million by the year 2000 (USA Ballast Book 1998).

Marine NIS invasions are a worldwide problem with economic and ecological consequences. Table 1 gives a few examples of marine NIS invasions worldwide and includes potential and proven impacts. These marine NIS demonstrate the variety of organisms that have invaded coastal habitats due to anthropogenic facilitation. Maritime shipping activity is blamed for the introduction of all the species listed, with the exception of *Caulerpa taxifola*, which was accidentally released from the Monaco Aquarium (Meinesz 1997). Incidentally, *Rapana venosa*, which was discovered in the southern Chesapeake Bay in 1998 (Harding and Mann 1999), was likely introduced from the Black Sea, where it is an alien species introduced from Japan. *Carcinus maenus* and *Asterias amurensis* both are likely to cause ecological changes, as epibenthic predators, in the areas in which they have been introduced (Grosholz and Ruiz 1995; Grannum et al. 1996). *Potamocorbula amurensis* has become the most numerous benthic invertebrate in its new habitat in San Francisco Bay, and could cause drastic changes due to its ability to filter out large quantities of plankton from the water column, thus changing the base of the food chain in this habitat (Cohen and Carlton 1995).

The species listed in Table 2 are examples of marine NIS that have invaded Hawaii. The macroalgae *Kappaphycus* and the snapper *Lutjanus kasmira* both were intentionally introduced, and appear to have effects on the communities in which they are present. *Chthamalus proteus* and *Gelliodes fibrosa* have both been reported recently, and are likely to have been present in Hawaii for some time (Southward et al. 1997; DeFelice 1999). These last two species are most likely introductions by commercial or military maritime shipping activities. Since *Chthamalus proteus* is native to the Caribbean, it is unlikely its larvae would have survived the journey to Hawaii in a ballast tank, and it was instead probably introduced as larvae from adult barnacles on a vessel hull. *Gelliodes fibrosa* is only known from the Philippines (DeFelice 1999), and was found on the hull of a floating drydock brought to Pearl Harbor from Subic Bay in the Philippines in 1992.

Species	*Area(s) and Date of Introduction*	*Native Range*	*Impacts*
Asterias amurensis (starfish)	Australia (1980's)	Japan, Korea	Negative economic impacts on shellfish industry
Carcinus maenus (crab)	North America -Atlantic Coast (late 1800's) -Pacific Coast (1990's) South Africa (1990's) Japan (1980's) Australia (1900's)	Western Europe, British Isles	Negative impacts on shellfish industry
Caulerpa taxifola (macroalgae)	Mediterranean (1980's)	West Indies	Negative impacts on local ecology due to overgrowth of habitats
Potamocorbula amurensis (clam)	North America -Pacific Coast (1980's)	Asia	Negative impacts on local ecology due to changes in food chain dynamics
Rapana venosa (snail)	North America -Mid-Atlantic (1990's)	Japan	Potential negative impacts on shellfish industry

Table 1. Examples of marine NIS introductions worldwide

HULL FOULING AS A MARINE NON-INDIGENOUS SPECIES PATHWAY

Ballast water is the pathway that has been the major focus of investigations concerned with marine invasion vectors, and the biofouling that occurs on the surfaces of vessel hulls has been given less attention. Historically, wooden

Species	*Area(s) and Date of Introduction*	*Native Range*	*Impacts*
Chtamalus proteus (barnacle)	Main Hawaiian Islands (after 1973)	Tropical Western Atlantic	Impacts not studied
Gelloides fibrosa (sponge)	Pearl Harbor,Oahu (recorded 1996)	Philippines	Impacts not studied
Chama macerophylla (oyster)	Pearl Harbor,Oahu (recorded 1996)	West Indies	Impacts not studied
Kappaphycus sp. (macroalgae)	Kaneohe Bay,Oahu (1970's)	Philippines	Overgrowth of coral reefs
Lutjanis kasmira (fish)	Oahu, Intentionally introduced (1950's)	Marquesas	Competition with native reef fish

Table 2. Examples of marine NIS introductions in Hawaii

sailing ships provided an ideal surface to which marine fouling organisms could attach. Common fouling organisms on these vessels were the wood-boring shipworms (*Teredo*). The cosmopolitan range of this organism is thought to have resulted from worldwide spread by wooden vessels, especially as trade routes opened up between the Atlantic and the Pacific. Hull fouling has been dramatically reduced with the advent of steel hulls and anti-fouling coatings. The steps taken by modern commercial and military vessels to eliminate hull fouling are not completely effective though, and organisms are still being transported by this means. Research surveys documenting modern day hull fouling organisms have been conducted periodically since the early 1900's, as follows:

- **Chilton 1910** – catalogued the fouling organisms from the hull of a British Antarctic ship in a dry dock in Lyttelton, New Zealand
- **Visscher 1928** - survey of 250 commercial and military vessels during shipyard service on the Atlantic coast of North America.
- **Ohshima et al., 1940 and 1943** - study of the fouling organisms on vessel hulls in Japan and their transport to other locations.
- **Edmondson 1944** - a record of hull fouling species occurring in Pearl Harbor, Hawaii.
- **Woods Hole Oceanographic Institution 1952** - study of hull fouling and its prevention for the U.S. Navy.
- **Allen 1953** - analysis of introduced fouling organisms in Australia associated with hull fouling transport.
- **Skerman 1960** - survey of 89 vessels in drydock arriving to New Zealand from regional and overseas destinations.
- **Doty 1961** – description of an invasive algae in Hawaii that was introduced by hull fouling.
- **Huang et al., 1979** - study of fouling organisms on vessel hulls in China and their transport to other locations.
- **Evans 1981** - investigation of the introduction of marine algae by hull fouling.
- **Callow 1986** - survey of marine algae transported by hull fouling.
- **Bagaveeva 1988** - study of polychaete worms in the hull fouling community of vessels arriving to Russian ports on the Sea of Japan.
- **Yan and Huang 1993** - hull fouling sampled from five vessels arriving to Daya Bay, China
- **Ranier 1995** - hull fouling samples from 8 vessels arriving to Tasmania.
- **Coutts 1999 –** survey of the distribution, abundance, and frequency of fouling communities on the hulls of 21 merchant vessels in Tasmania.
- **DeFelice and Godwin 1999 –** identification of the hull fouling organisms on the hull of the USS Missouri after being towed to Pearl Harbor, Hawaii from Bremerton, Washington.
- **James and Hayden 2000 –** study of the hull fouling communities of 12 commercial vessels and 27 overseas yachts in New Zealand .
- **Godwin and Eldredge 2001 –** survey of the hull fouling organisms present on 7 overseas barges and a floating dry dock arriving to Hawaii during the South Oahu Marine Invasion Shipping Study.
- **Floerl 2001 –** examination of hull fouling on recreational vessels in Queensland, Australia and how marina design might enhance recruitment of non-indigenous fouling species.

ORGANISMS ASSOCIATED WITH HULL FOULING

The organisms that generally foul vessel hulls are the typical species found in natural marine intertidal and subtidal fouling communities. The surveys listed above have reported typical invertebrate phyla associated with marine fouling communities such as arthropoda (barnacles, amphipods, and crabs), mollusca (mussels, clams, and sea slugs), porifera (sponges), bryozoa (moss animals), coelenterata (hydroids and anemones), protozoa, annelida (marine worms), and chordata (sea squirts and fish), as well as macroalgae (seaweed). Fouling organisms tend to concentrate in sheltered areas of the hull, such as sea chest intakes and rudder posts, and develop in areas where anti-fouling coatings have been compromised (Ranier 1995; Coutts 1999; Godwin personal observation). Anti-fouling coatings wear off along the bilge keel and weld seams, and are inadequately applied in some cases, which makes the surfaces susceptible to settlement by fouling organisms.

Two recent marine NIS introductions to Hawaii are directly attributed to hull fouling. The bivalve mollusk *Chama macerophylla* and the sponge *Gelliodes fibrosa* both were introduced from the fouling community on the hull of a floating drydock towed to Hawaii from the Philippines in 1992 (DeFelice 1999). The barnacle *Chthamalus proteus*, which was mentioned earlier, is native to the Caribbean, and was not recorded in Hawaii before 1973 (Southward et al. 1998). As stated earlier, this barnacle was likely introduced by larvae spawned from adults that were part of a hull fouling community. Apte et al. (2000) recorded such a scenario with blue mussels (*Mytilus galloprovincialis*), which were part of the fouling community on the hull of the U.S.S. Missouri, which was towed to Pearl Harbor from Bremerton, Washington. These mussels, which are NIS to Hawaii, were observed spawning upon arrival to Pearl Harbor; three months later, settled juveniles were recorded in the harbor, and identified as *Mytilus galloprovincialis* through molecular techniques.

SOUTH OAHU MARINE INVASIONS SHIPPING STUDY (SOMISS) – HULL FOULING SURVEY

As mentioned earlier, the SOMISS project was conducted to determine if the maritime shipping industry in Hawaii acts as a pathway for introducing marine NIS. SOMISS surveyed the maritime shipping industry in Hawaii by collecting biological and operational data that would relate to the issue of marine NIS invasion. The operational aspect identified what types of vessels use Hawaii as a port, what unloading/loading operations are being conducted, what ballasting/deballasting operations are being conducted, and from what regions the vessels are arriving. Biological data for organisms being transported by vessels encompassed three vectors: ballast water, ballast water sediments, and hull fouling.

The SOMISS project showed that Hawaii is a net importer of manufactured goods and bulk materials, thus it receives less ballast water discharge than port systems that are net exporters of these cargoes. Ballast water is still discharged in the port system of Hawaii, and still remains a potential pathway for marine NIS, but other pathways should also be considered. Historical information reviewed during the SOMISS project points towards hull fouling as a vector of great importance as a pathway for marine NIS in Hawaii (Eldredge and Carlton, In preparation).

If the coatings applied to the hulls of modern commercial vessels are maintained, they act as a deterrent to the settlement of marine organisms on vessel surfaces below the water line. Studies such as Ranier (1995) and Coutts (1999) have shown that there are areas on the hull where the coatings are compromised, thus allowing settlement of marine fouling organisms. Field observations in dry docks by the author have revealed that the anti-fouling coatings do not adhere as well along weld seams, and allow fouling growth in these areas. When vessels are in dry dock large wooden blocks are used to support them. Coutts (1999) has shown that these blocks prevent complete coverage of anti-fouling coatings when vessel hulls are repainted in shipyards. Fouling organisms have also been noted to exist in sheltered areas around rudder posts, and within sea chest intakes. Sea chest intakes tend to harbor a diverse community that is sheltered from the turbulence created by movement through the water. Even properly maintained vessels can transport fouling organisms when these factors exist.

Slow moving vessels that have long residence times in port are more likely to develop fouling organisms, than those that have short residence times, and are transiting more often. Towed vessels, such as, overseas cargo barges, floating dry docks, vessels from decommission yards, or any floating platform, are examples of this type of dynamic. Hawaii relies on towed cargo barges for a percentage of overseas imports, and they are used exclusively for weekly interisland cargo transport. Floating dry docks and vessels from decommission yards are less frequent, but represent a large scale threat for transporting marine NIS within hull fouling communities. Since Hawaii is the “Crossroads of the Pacific”, it tends to be the port of call for the refueling and maintenance of vessels transiting between Asia and the Americas. The tug boats towing these vessels across the vast expanse of the Pacific are likely to use Hawaii as a port of call for fuel, supplies, or repairs. This creates a scenario that allows the port of entry to be exposed to the fouling organisms present on the hull of the towed platform. Towed cargo barges that make port call in Hawaii, and a single floating dry dock were the focus of the SOMISS hull fouling survey.

Sampling Methodology

Surveys for adult invertebrates that were part of the hull fouling communities were done to determine the extent marine NIS species are being transported in this fashion. The focus was to perform a qualitative analysis and generate a species list of all organisms with the source location of the vessel from which they were

sampled. A total of 8 vessels, made up of 7 overseas cargo barges and
1 floating dry dock, were surveyed during the study. Two divers, swimming from bow to stern on the port and starboard side, conducted the hull fouling surveys. The surveys involved sampling of each type of organism seen during the dive, and removing it with scrapers and chisels. These organisms were returned to the laboratory and preserved for later identification.

The source regions for the vessels sampled were obtained from the vessels directly or from the shipping agents that handled each vessel. The geographic scheme for recording the source locations was based on the United Nations Food and Agriculture Organization (FAO) regions for the waters of the world.

Results

All of the species identified during the study are shown in Table 3. The organisms represent 8 phylum of both plants and animals: Plantae (plants), Porifera (sponges), Cnidaria (anemones, corals), Annelida (marine worms), Mollusca (clams, sea slugs, worm shells) Crustacea (crabs, amphipods, and crabs), Bryozoa (moss animals), and Chordata [subphylum Urochordata] (sea squirts).

The plants were totally represented by macroalgae, which was made up of 14 species of Rhodophyta (red algae), 9 species of Chlorophyta (green algae), and 3 species of Phaeophyta (brown algae). The sponges were represented by 3 species that could not be identified due to the taxonomic difficulties with this group. There were 9 species of marine worm, of which 6 were unidentified. A total of 6 species of oyster and clam, 1 sea slug, 3 snails, and 1 worm shell made up the sample of mollusc species from the various vessels. Crustaceans were well represented by 11 barnacle species, 3 amphipods, 2 isopods, and 3 crabs. There was a total of 8 Bryozoans, or moss animals, and two of these were unidentified. Finally, 7 different species of Ascidiacea, or sea squirt, were identified from the samples. Table 3 shows the species that were identified, and includes the FAO source region of the vessel from which they were sampled, as well as the status of the species in Hawaii (ie., native, introduced, unknown)

The vessels sampled originated from 4 source regions based on the FAO scheme: WCP (West Central Pacific), ECP (East Central Pacific), NEP (North East Pacific), and a HI category for interisland vessels operating in Hawaii. Figures 1 and 2 show the NIS species recorded by taxonomic group, and the associated FAO source region for the vessels from which the samples were taken.

CONCLUSION

There are three ports in the Hawaiian Islands that are the hub of maritime shipping traffic. These ports are Honolulu Harbor, Pearl Harbor, and Barber's Point Harbor. These are the main areas for potential marine NIS invasions facilitated by maritime shipping activities. This would also create a situation in which these ports would act as points of establishment, and further spread of marine NIS to the remainder of the Hawaiian Archipelago.

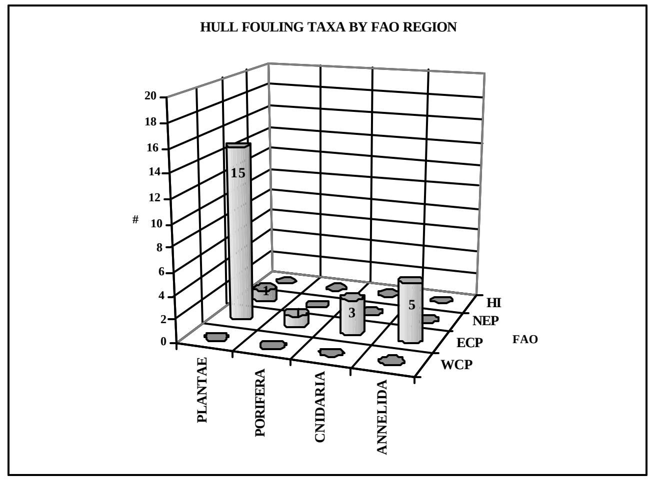

Figure 1. Number of NIS by FAO region for Plantae, Porifera, Cnidaria, and Annelida.

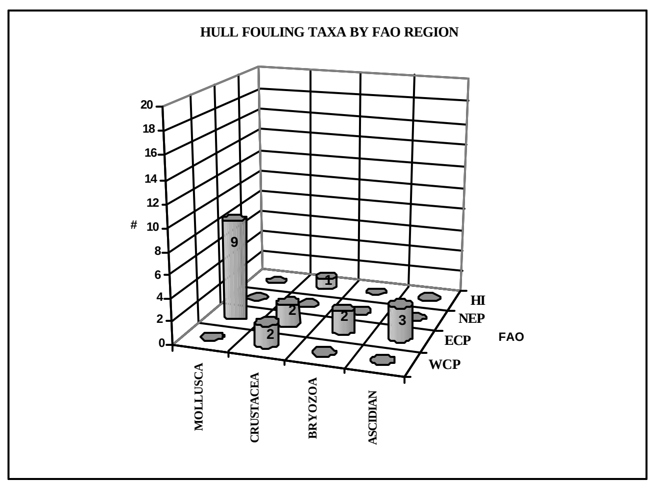

Figure 2. Number of NIS by FAO region for Mollusca, Crustacea, Bryozoa, and Ascidia.

The majority of vessels surveyed during SOMISS had low levels of fouling by maritime industry standards. Despite the low fouling level, marine NIS that have previously been documented for Oahu were found

Taxa	Group	Genus & Species	Vessel Source Region	Specific Vessel Source Location	Hawaii Status
PLANTAE	Rhodophyta	*Aglaothamnion cordatum*	ECP	California	NIS
		Amphiroa sp.	HI	Interisland	Native
		Antithamnion hubbsii	ECP	California	NIS
		Antithamnion sp.	ECP	California	NIS
		Brachioglossum woodii	ECP	California	NIS
		Callithamnion acutum	ECP	California	NIS
		Ceramium gardneri	ECP	California	NIS
		Ceramium sp.	ECP	California	Native
		Dasya sinicola	ECP	California	NIS
		Grateloupia sp.	ECP	California	NIS
		Halymenia sp.	ECP	California	NIS
		Pterosiphonia bipinnata	ECP	California	NIS
		Rhodoptilum plumosum	ECP	California	NIS
		Schizymenia dawsonii	ECP	California	NIS
	Chlorophyta	*Enteromorpha clathrata*	HI, NEP	Interisland, Oregon	Native
		Enteromorpha clathrata (variation *crinata)*	ECP	California	NIS
		Enteromorpha intestinalis	ECP	California	Native
		Enteromorpha prolifera	NEP	Washington	Native
		Enteromorpha sp.	WCP, ECP	Marshall Islands, California	Native
		Feldmania indica	NEP	Washington	Native
		Hincksia mitchelliae			
		Hincksia sp.	HI	Interisland	Native
		Pilayella sp.	NEP	Oregon	NIS
		Ulva rigida	ECP	California	Native
	Phaeophyta	*Dictyota flabellata*	ECP	California	NIS
		Sargassum muticum	ECP	California	NIS
PORIFERA					
		Unidentified Species	HI	Interisland	Unknown
		Unidentified Species	HI	Interisland	Unknown
		Unidentified Species	ECP	California	NIS(?)
CNIDARIA	Hyrozoa	*Obelia dichotoma*	ECP	California	Native
		Unknown Species	ECP	California	NIS(?)
	Anthozoa	*Diadumene leucolena*	ECP	California	NIS
		Corynactus californica	ECP	California	NIS
		Balanophyllia elegans	ECP	California	NIS
ANNELIDA	Syllidae	Unknown Species	ECP	California	NIS(?)
	Nereidae	Unknown Species	HI	Interisland	Unknown
		Unknown Species	ECP	California	NIS(?)
	Serpulidae	*Hydroides sp.*	HI, WCP	Interisland, Marshall Islands	Native
		Unknown Species	ECP	California	NIS(?)
	Sabellidae	Unknown Species	ECP	California	NIS(?)
	Polynoidae	Unknown Species	ECP	California	NIS(?)
Key: ECP=East Central Pacific, NEP=North East Pacific, WCP=West Central Pacific, HI= Hawaiian Islands, NIS=alien to Hawaii, NIS(?)=unknown status, Native=native to Hawaiian Islands					

Table 1. Organisms recorded during hull fouling survey

Taxa	Group	Genus & Species	Vessel Source Region	Specific Vessel Source Location	Hawaii Status
MOLLUSCA	Gastropoda	*Crepidula sp.*	HI, WCP	Interisland, Marshall Islands	Native
		Crepidula onyx	ECP	California	NIS
		Crepidula lingulata	ECP	California	NIS
	Bivalvia	*Ostrea sandvichensis*	HI, WCP	Interisland, Marshall Islands	Native
		Mytilus galloprovincialis	ECP	California	NIS
		Ostrea conchaphilia	ECP	California	NIS
		Protothaca laciniata	ECP	California	NIS
		Pseudochama sp.	ECP	California	NIS
		Musculus sp.	ECP	California	NIS
CRUSTACEA	Cirrepedia(Barnacles)	*Chthamalus proteus*	HI, WCP, ECP, NEP	Interisland, Marshall Islands, Calififornia, Oregon	NIS
		Euraphia hembelii	HI, WCP	Interisland, Marshall Islands	Native
		Nesochthamalus intertexus	WCP	Marshall Islands	Native
		Tesseropora pacifica	WCP	Marshall Islands	Native
		Megabalanus californicus	WCP, ECP	Marshall Islands, California	NIS
		Balanus reticulatus	HI	Interisland	Native
		Balanus amphitrite	HI, ECP,NEP	Interisland, California	NIS(?)
		Megabalanus tanagrae	HI	Interisland	Native
		Conchoderma virginatum	ECP	California	Native
		Conchoderma auritum	ECP	California	Native
		Lepas anatifera	ECP, NEP	California, Oregon	Native
	Amphipoda	*Jassa falcata*	WCP	Marshall Islands	NIS
		Hyale laie	NEP	Oregon	Native
		Jassa lilipuna	NEP	Oregon	Native
	Isopoda	*Anatanais in sularis*	WCP	Marshall Islands	Native
		Sphaeroma sp.	ECP	California	NIS(?)
	Decapoda	*Plagusia immaculata*	ECP	California	Native
		Pachygrapsus crassipes	ECP	California	Native
		Pilumnus oahuensis	ECP	California	Native
BRYOZOA		Unidentified Species	HI	Interisland	Native
		Unidentified Species	HI	Interisland	Native
	Bugulidae	*Bugula flabellata*	ECP	California	NIS
		Bugula stolonifera	ECP	California	Native
		Bugula neritina	ECP	California	Native
	Vesicullariidae	*Zoobotryon verticillatum*	ECP	California	Native
	Celleporariidae	*Celleporaria brunnea*	ECP	California	NIS
	Schizoporelliidae	*Schizoporella unicornus*	ECP	California	Native
ASCIDIACEA	Perophoridae	*Perophora annectens*	ECP	California	Native
	Styelidae	*Symplegma reptans*	ECP	California	NIS
		Botryllus simodensis	ECP	California	Native
		Botryllus perspicuus	ECP	California	NIS
		Styela canopus	ECP	California	Native
	Pyuridae	*Microcosmus exasperatus*	HI	Interisland	Native
		Microcosmus squamiger	ECP	California	NIS

Key: ECP=East Central Pacific, NEP=North East Pacific, WCP=West Central Pacific, HI= Hawaiian Islands, NIS=alien to Hawaii, NIS(?)=unknown status, Native=native to Hawaiian Islands

Table 1. (continued)

regularly on interisland cargo barges. These vessels may be acting as agents for the further dispersal of some alien species to the other main islands.

The introduced barnacle *Chthamalus proteus* was present in great numbers on the two interisland cargo barges surveyed. This may explain its presence on all of the main islands of Hawaii, except Kaho'olawe, which is a nature and cultural reserve, and requires vessels to be inspected for alien species before their arrival to the island. This barnacle was also present on barges arriving to Honolulu Harbor from California and the Pacific Northwest. These particular barges are on regularly scheduled routes between ports along the United States West Coast and Hawaii. *Chthamalus proteus* has settled on the hulls of these vessels during their unloading periods in Hawaii, which has turned these vessels into a potential vector for the introduction of this barnacle to ports in California, Oregon, and Washington. This is also the case for the regular cargo barge service between Hawaii and the Marshall Islands, which is another isolated marine environment.

The largest source region for hull fouling species listed in Table 1 was the ECP region. This was due to a single floating dry dock that was towed from San Diego to Barber's Point Harbor, which had a high abundance of fouling. The most serious hull fouling vectors are vessels that are poorly maintained or have been inactive for long periods. This dry dock fit this description because it had been moored for a long period of time in the San Diego area, and had an extensive fouling community. Efforts should be made by harbor authorities to monitor vessel traffic of this type, and recognize the potential for NIS introductions. Hull fouling must receive greater attention as a pathway for marine NIS introductions in the Hawaiian Islands, and other port systems throughout the world. Extreme focus is presently placed on ballast water as a marine invasion pathway, but all the pathways associated with maritime shipping should be considered together for monitoring and management strategies concerned with the prevention of marine NIS introductions. Legislation concerning this issue needs to broaden its scope and consider all pathways associated with maritime shipping.

The South Oahu Marine Invasion Shipping Study was focused on a suite of mechanisms associated with maritime shipping which contribute to an overall pathway for marine NIS introductions. This study has shown that viable organisms exist in association with ballast water, ballast water sediments, and hull fouling, and are being transported to the Hawaiian Islands. In the Hawaiian Islands, there is no completely encompassing legislation that would provide guidance for the port authorities to make decisions about marine NIS prevention. Collaborative efforts by the State of Hawaii Department of Transportation and Department of Land and Natural Resources, the commercial shipping industry, the United States Coast Guard, and the scientific community will be needed to guard against future marine NIS introductions.

Awareness of the marine NIS issue and its connection to maritime shipping activities, both domestic and international, will be an important component in the future efforts in protecting the marine environment of Hawaii in the face of a growing global economy.

LITERATURE CITED

Allen F. E. 1953. Distribution of marine invertebrates by ships. *Australian Journal of Marine and Freshwater Research* 4(2):307-316.

Apte, S., B.S. Holland, L.S. Godwin, and J.P.A. Gardner. 2000. Jumping ship: a stepping stone event mediating transfer of nonindigenous species via a potentially unsuitable environment. *Biological Invasions* 2: 75-79.

Bagaveeva, E. V. 1988. Polychaetes in foulings of ships plying the coasts in the northwestern part of the Sea of Japan. *Soviet Journal of Marine Biology* 14:22-26.

Callow, M. E. 1986. Fouling algae from "in service" ships. *Botanica Marinus* 29:351-357.

Carlton, J. T. 1993. Biological invasions and biodiversity in the sea: The ecological and human impacts of nonindigenous marine and estuarine organisms. In: *Proceedings of the Conference and Workshop: Nonindigenous Estuarine and Marine Organisms (NEMO)*.

Carlton, J.T., and J.B. Geller.1993. Ecological roulette: Biological invasions and the global transport of non-indigenous marine organisms. *Science* 261:78-82.

Carlton, J.T., D. Reid and H. van Leeuwen. 1995. *The Role of Shipping in the Introduction of Nonindigenous Aquatic Organisms to the Coastal Waters of the United States (other than the Great Lakes) and the Analysis of Control Options*. Report to the U.S. Coast Guard, Marine Environmental Protection Division, Washington, DC. 215pp.

Chilton, C. 1910. Notes on the dispersal of marine crustacea by means of ships.*Transactions of the New Zealand Institute.* 43:131-133.

Cohen, A. N. and J. T. Carlton. 1995. *Biological Study. Nonindigenous Aquatic Species in a United States Estuary: A Case Study of the Biological Invasions of the San Francisco Bay and Delta.* U. S. Fish and Wildlife Service, Washington, D. C. and the National Sea Grant College Program, Connecticut Sea Grant, NTIS No. PB96-166525.

Coutts, A.D.M. 1999. *Hull fouling as a modern vector for marine biological invasions: investigation of merchant vessels visiting northern Tasmania*. M.S. Thesis. Faculty of Fisheries and Marine Environment, Australian Maritime College.

DeFelice, R.C. 1999. Fouling marine invertebrates on the hull of the *USS Machinist* in Pearl Harbor prior to its move to Apra Harbor, Guam. Final report submitted to U.S. Fish and Wildlife Servive, Pacific Islands Ecoregion, Honolulu, Hawaii. Hawaii Biological Survey contribution 1999-013.

DeFelice, R.C. and L.S. Godwin. 1999. Records of marine invertebrates in Hawaii from the hull of the *USS Missouri* in Pearl Harbor, Oahu. *Bishop Museum Occasional Papers* 59:42-45.

Doty, M.S. 1961. *Acanthophora*, a possible invader of marine flora of Hawaii. *Pacific Science* 15: 547-552.

Edmondson, C. H. 1944. Incidence of fouling in Pearl Harbor. *Bernice P. Bishop Museum Occasional Papers* 18, 34 pp.

Eldredge, L.G. and J.T. Carlton. In Preparation. Marine Bioinvasions of Hawaii: the introduced and cryptogenic marine and brackish water animals and plants of the Hawaiian Archipelago.

Evans, L. V. 1981. Marine algae and fouling: a review, with particular reference to ship fouling. *Botanica Marinus* 24:167-171.

Floerl, O.and G.J. Inglis. 2001. Human influences on the contagion of nonindigenous marine species in boat harbors. *Proceedings of the International Conference om Marine Bioinvasions, New Orleans, April 9-11 2001*.

Godwin, L.S. and L.G. Eldredge. 2001. *The South Oahu Marine Invasion Shipping Study*. Final report prepared for the Hawaii Department of Land and Natural Resources, Division of Aquatic Resources. Bishop Museum Technical Report No. 20.

Grannum, K., N.B. Murfet, D.A. Ritz, and E. Turner. 1996. The distribution and impact of the exotic seastar *Asterias amurensis*, in Tasmania. In: *The introduced northern Pacific seastar, Asterias amurensis in Tasmania.* Australian Nature Conservation Agency: Canberra.

Grosholz, E.D. and G.M. Ruiz. 1995. Spread and potential impact of the recently introduced European green crab, *Carcinus maenas*, in central California. *Marine Biology* 122:239-247.

Harding, J. M. and R. Mann. 1999. Observations on the biology of the veined rapa whelk, *Rapana venosa* Valenciennes 1846, in Chesapeake Bay. *Journal of Shellfish Research* 18(1):9-17.

Huang, X. M., W. Z. Ni, H. Q. Lu, and K.D. Lui. 1979. A study of the interrelation between service condition of ships and fouling organisms. *Oceanologia et Limnologia Sinica* 10:82-9.

James, P. and B. Hayden. 2000. *The potential for the introduction of exotic species by vessel hull fouling: a preliminary study*.NIWA Client report No.WLG 00/51. NIWA Wellington, NZ.

Meinesz, A. 1997. *Killer Algae: the true tale of a biological invasion.* University of Chicago Press, Chicago, IL, 360pp.

Nalepa, T. F. and D. W. Schloesser (eds). 1992. *Zebra Mussels: Biology, Impacts, and Control*. Lewis Publishers, Inc. (CRC Press), Boca Raton, FL., pp. 677-697.

National Research Council. 1996. *Stemming the Tide: Controlling introductions of nonindigenous species by ship's ballast water.* National Academy Press, Washington, D.C. 141pp.

Office of Technology Assessment. 1993. *Harmful Nonindigenous Species in the United States.* OTA-F-565.

Ohshima, H., S. Miyake, K. Arita, and S. Murakami. 1940. Fundamental study of fouling organisms on the bottom of ships. *Naval Institute of Technology, Japan* 786:1-49.

Ohshima, H. and S. Miyake. 1943. Geagraphical distribution of fouling animals of ship bottoms. *Naval Technology Institute of Japan* 387:1-7.

Ranier, S. F. 1995. *Potential for the Introduction and Translocation of Exotic Species by Hull Fouling: A Preliminary Assessment*. Centre for Research on Introduced Marine Pests Technical Report No. 1. Hobart, Tasmania.

Skerman, T. M. 1960. Sip-fouling in New Zealand waters: a survey of marine fouling organisms from vessels of the coastal and overseas trade. *New Zealand Journal of Science* 3:377-378.

Smith, L. D., M. J. Wonham, L. D. McCann, D. M. Reid, J. T. Carlton, and G. M. Ruiz. 1996. *Shipping Study II: Biological Invasions by Nonindigenous Species in Unites States Waters: Quantifying the Role of Ballast Water and Sediments, Parts I and II.* Report No. CG-D-02-97, U. S. Coast Guard, Groton CT, and U. S. Department of Transportation, Washington, D. C.

Southward, A. J., R. S. Burton, S. L. Coles, P. R. Dando, R. DeFelice, J. Hoover, P. E. Parnell, T. Yamaguchi, and W. A. Newman. 1998. Invasion of Hawaiian shores by an Atlantic barnacle. *Marine Ecology Progress Series* 165:119-126.

USA Ballast Book. 1998. *Ballast Research in the United States of America*. Prepared for the International Council for the Exploration of the Sea (ICES), United Nations International Maritime Organization (IMO), Intergovernmental Oceanographic Commission (IOC) Study Group on Ballast Water and Sediments, and the United Nations IMO Working Group on Ballast Water. 204 pp.

Visscher, J. P. 1928. Nature and extent of fouling of ships' bottoms. *Bulletin of the Bureau of Fisheries* 43(2): 193-252.

Vitousek, P.M., L.L. Loope, and C.P. Stone. 1987. Introduced species in Hawaii: biological effects and opportunities for ecological research. *Trends Ecol. Evol*. 2(7):224-227.

Williams, R. J., F. B. Griffiths, E. J. van der Wal, and J. Kelly. 1988. Cargo vessel ballast water as a vector for the transport of nonindigenous marine species. *Estuarine and Coastal Shelf Science* 26:409-420.

Woods Hole Oceanographic Institution. 1952. Marine fouling and its prevention. *United States Naval Institute*, Annapolis, MD, 338 pp.

Wonham, M.J., J.T. Carlton, G.M. Ruiz, and L.D. Smith. 2000. Fish and ships: relating dispersal frequency to success in biological invasions. *Marine Biology* 136:1111-1121.

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