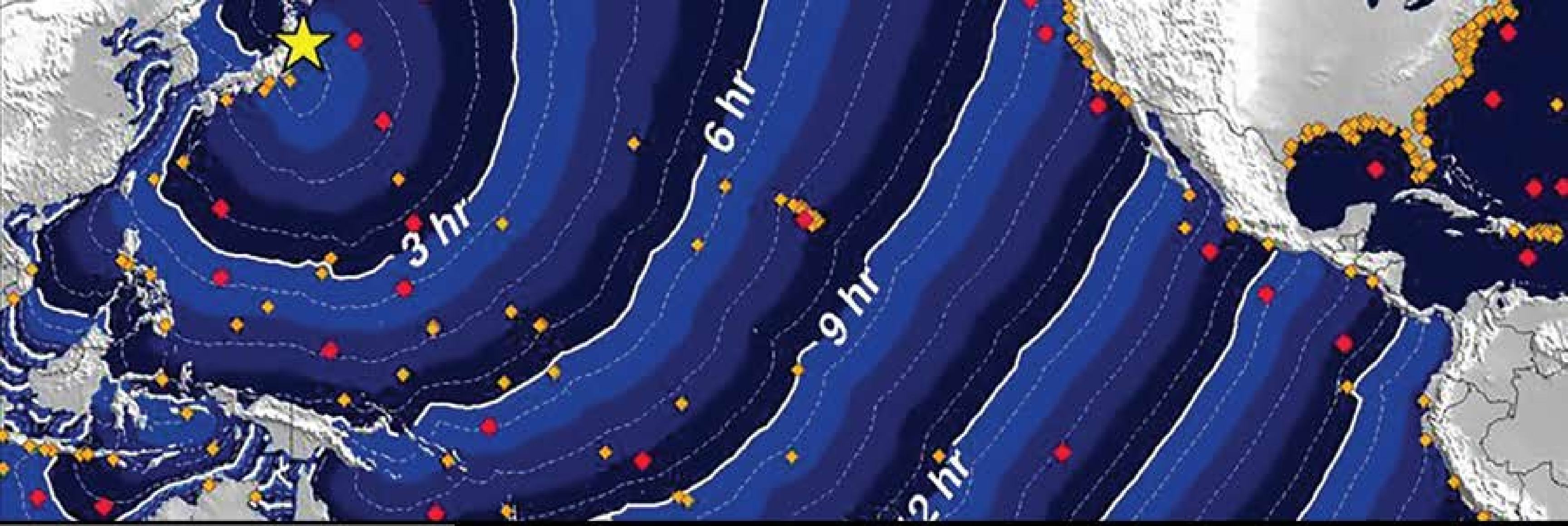
The effects of marine debris caused by the Great Japan Tsunami of 2011



PICES SPECIAL PUBLICATION 6

The Effects of Marine Debris Caused by the Great Japan Tsunami of 2011

The PICES ADRIFT project was a rare and exciting interdisciplinary study, and we are extremely grateful to the people and the government of Japan for their vision and support while rebuilding and recovery efforts continue in Japan. With more than 40 researchers from 30 institutions working in three countries, this research yielded unusual insight into physical and biological oceanography, biogeography, taxonomy, ecology, genetics, and the strength of the human spirit. Research funding was provided by the Japanese Ministry of the Environment through the North Pacific Marine Science Organization (PICES).

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PICES SPECIAL PUBLICATION 6

The Effects of Marine Debris Caused by the Great Japan Tsunami of 2011

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Ministry of the Environment
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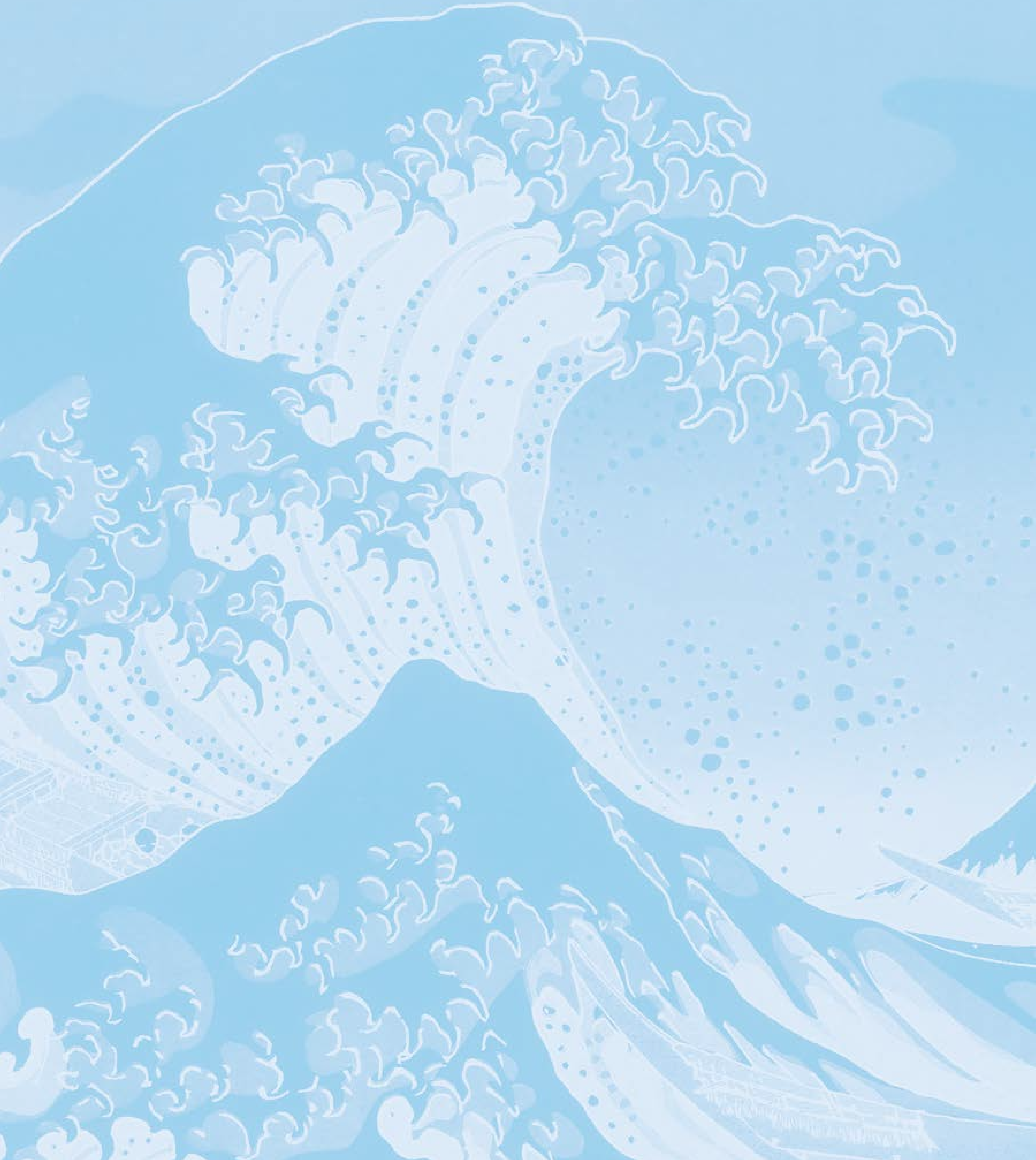
Front cover images: (Top): Computed tsunami arrival times, March 11, 2011 (Honshu, Japan). Credit: National Tsunami Warning Center, NOAA/NWS. (Bottom): Aerial view of tsunami debris, northern Japan, taken March 13, 2011. Credit: U.S. Navy.



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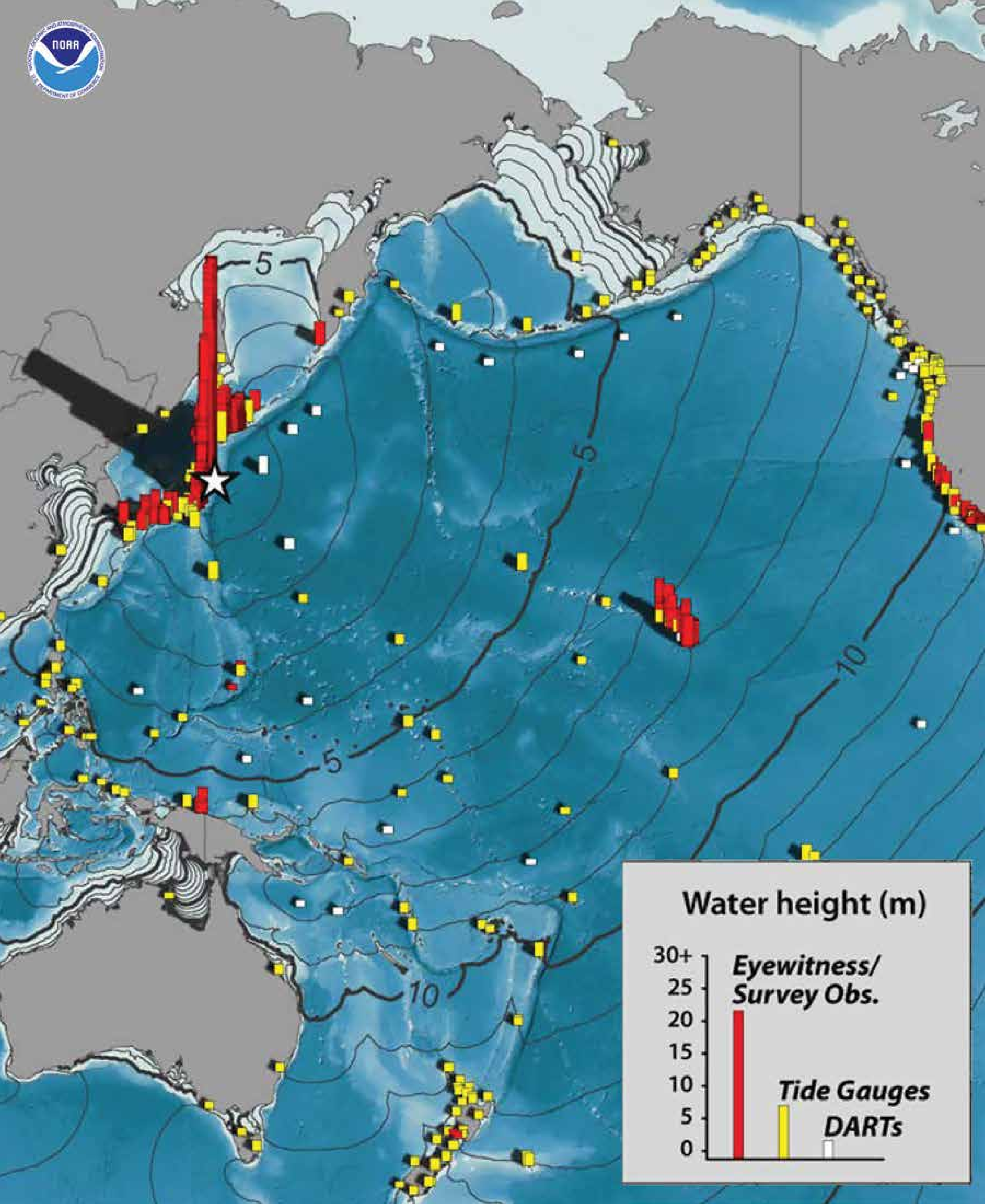
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National Tsunami Warning Center, NOAA/NWS

Executive Summary

The Great East Japan Earthquake, with magnitude 9.1, struck off the Tohoku coast on March 11, 2011, and triggered a massive tsunami that surged inland across kilometers of shoreline. This event was a natural disaster of staggering proportions, causing loss of human life, property destruction, and environmental damage. The tsunami washed millions of tons of material into the Pacific Ocean and, within a year, this debris (termed Japanese Tsunami Marine Debris or JTMD), carrying living coastal Japanese species, began arriving on the shores of the Pacific coast of North America and the Hawaiian Islands (hereafter Hawaii). The overall goal of a 3-year (2014–2017) PICES project, funded by the Ministry of the Environment (MoE) of Japan, was to assess and forecast the potential effects of JTMD, especially those related to non-indigenous species (NIS), on ecosystem structure and function, the coastlines, and communities along the Pacific coast of North America and Hawaii, and to suggest research and management actions to mitigate any impacts.

The JTMD study provided the first opportunity in the history of marine science to track a multi-year large-scale (7000+ km) transoceanic rafting event of marine life originating from an exact known source and with an exact known sea-entry time. The project, referred to as ADRIFT (**A**ssessing the **D**ebris-**R**elated **I**mpact **F**rom the **T**sunami), brought together researchers from multiple scientific disciplines, and this international team focused on three major themes: (1) modeling movement of marine debris in the North Pacific to forecast and hindcast JTMD trajectories and landings, (2) surveillance and monitoring of JTMD landfall and accumulation, and (3) characterizing and assessing the invasion risk of NIS transported on JTMD.

The *modeling group* employed a suite of general circulation models, validated and scaled using available observational reports, to simulate the movement of marine debris and to forecast the distribution of JTMD and timelines of its potential arrival on the Pacific coast of North America and in Hawaii. Model solutions suggest that during the eastward drift across the North Pacific the debris is "stratified" by the wind such that light-weight floating debris (e.g., polystyrene materials) is transported rapidly, sometimes reaching North America within a year following the tsunami, while heavier partially submerged or sunken debris could remain in the ocean considerably longer, with the potential to become trapped in the part of the Subtropical Gyre known as the "garbage patch." Model predictions agree with the types of JTMD reported from different areas and timelines of its arrival on the North American and Hawaiian coasts, exhibiting strong seasonal and interannual variations. New modeling techniques were also developed to derive probable drift trajectories of individual JTMD items to highlight areas where debris was likely to accumulate, and to evaluate the oceanographic conditions (temperature, salinity, etc.) along the JTMD pathways where Japanese coastal species could potentially survive transit, thereby facilitating NIS risk assessments.

Analysis of the temporal and spatial variability in JTMD landfall in North America and Hawaii by the *surveillance and monitoring group* demonstrated a sharp and significant increase in debris influx beginning in May 2012; the detection of indicator items, such as beverage containers and other consumer objects, suggested a 10-fold increase in beached debris over pre-tsunami levels. It was also found that debris influx differed by coastline, with higher-windage debris being transported to higher latitudes. Recognizing the existence of vast, uninhabited areas where JTMD could have made landfall, systematic aerial photographic surveys were conducted to search for, and quantify, JTMD arriving on the coastlines of British Columbia (BC) and Hawaii. The surveys were the first comprehensive debris evaluations in these two regions, providing an important baseline of marine debris and complementing previous similar efforts in Alaska. In February 2015, a webcam system was installed at a site in Oregon to track beach-specific debris landings and removals to better understand the temporal dynamics of debris on coastal beaches.

The *NIS group* examined the invasion potential of species associated with JTMD by documenting the biodiversity allied with arriving JTMD objects, formally evaluating the risk of the species and JTMD as a vector for NIS overall, and by conducting detection surveys in Pacific North America and Hawaii. Since the summer of 2012, over 630 JTMD items were intercepted and sampled, from which more than 370 species of algae, invertebrates and fish have been identified. In some cases, molecular techniques were needed to fully resolve species identity. Genetic analyses on selected JTMD macroalgae confirmed the source location as the Tohoku region and ruled out secondary settlement from elsewhere in the Pacific. Surprisingly, many species rafting on JTMD grew while at sea and had the potential to be reproductive upon arrival on the coasts of Hawaii and the Eastern Pacific. With time, fewer species arrived alive, but even as of spring 2017 living Japanese species were still documented arriving on JTMD objects.

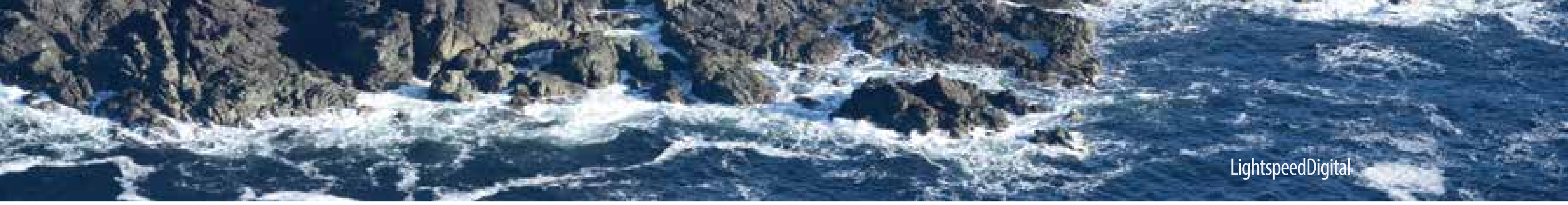
Lori Waters

The invasion risk of species associated with JTMD was characterized using a screening-level risk assessment tool – the Canadian Marine Invasive Screening Tool (CMIST). Higher-risk invertebrates (some well-known global invaders) were identified for each Pacific North American and Hawaiian ecoregion (unique biogeographic areas with different species composition) that received debris. Overall, risk varied by region, with the highest median risk given to northern California (an area that already hosts a number of NIS from historical vectors such as shellfish aquaculture and commercial shipping), and the highest cumulative risk given to Hawaii (an area that has the largest number of novel JTMD species because of its unique flora and fauna). A Top 10 Watch List was produced for each ecoregion. By synthesizing life history and tolerance traits for JTMD species, it was found that more than 30 relatively unknown Japanese species have traits similar to those with prior invasion histories, and may pose additional risks.

Detection surveys (fouling panel deployment, mussel parasite screening and visual inspections) were carried out at more than 130 sites in each affected ecoregion in an effort to detect the establishment of invertebrate and algae species associated with JTMD. These surveys conducted through to 2017 have not detected a single establishment event but are serving as important baselines for future monitoring efforts as NIS introductions can take years to decades to detect. Likewise, the potential influx of new genetic material for species already present in North America and Hawaii from more traditional invasion vectors should not be ignored.

Based on this extensive body of research, a number of conclusions can be drawn about the impact of marine debris from the Great Japan Tsunami of 2011. A substantial amount of debris arrived on the Pacific shorelines of North America and Hawaii from 2012 to 2017 that can be directly attributed to this event. An unknown portion of JTMD remains afloat in the North Pacific Ocean and may continue to arrive for years to come. The volume of this original pulse of debris is of a similar magnitude to that entering the oceans from other sources on an annual basis, although the object types, species composition, and trajectories of JTMD differ in many ways.

The biodiversity of Japanese coastal species documented on recovered JTMD items was diverse. This has been the most intensely scrutinized group of species, with more than 80 taxonomists contributing to the identification effort. Overall, there is little doubt that JTMD represents a novel transport vector for potentially invasive species to North America and Hawaii. However, given its one-time nature, JTMD could be considered a lower risk when compared to other historical and contemporary ongoing vectors like commercial shipping, where the cumulative risk is substantially higher. Nevertheless, JTMD served to significantly raise global awareness of the potential role of marine debris in species dispersal.



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The ADRIFT project produced a remarkable number of publications and legacy products. To date, key publications (all Open Access) include: a synthesis of the JTMD vector in *Science* (September 2017, Vol. 357, No. 6358, pp. 1402–1406)[1] and two journal special issues – one with papers focused on the taxonomy of JTMD species published in *Aquatic Invasions* (February 2018, Vol. 13, Is. 1, pp. 1–186)[2], and the other with papers on modeling, surveillance, monitoring, ecology and invasion risk of species published in *Marine Pollution Bulletin* (July 2018, Vol. 132, pp. 1–106)[3].

The following legacy products from the project are available to the scientific community and public:

1. *The JTMD species database*[4] on the Smithsonian Institution online portal NEMESIS (National Exotic Marine and Estuarine Species Information System) provides information on the distribution, biology, ecology, life history traits and invasion history for selected species of marine invertebrates and algae from the northwestern Pacific Ocean, including those associated with JTMD, and is an important resource contributing to risk assessments;
2. *The archival collection of marine invertebrate specimens from JTMD* housed at the Royal British Columbia Museum (Victoria, Canada) and *the archival collection of JTMD algae* residing at the Oregon State University Herbarium (Corvallis, USA) will allow researchers world-wide to access these unique resources now and in the years to come, especially with the advance of new analytical techniques;
3. *Products (photographs, debris ranking segments and maps) from the 2014 and 2015 aerial surveys of the exposed outer coast of British Columbia* can be accessed through an online mapping portal designed and hosted by the BC Provincial Government (PICES Tsunami Debris Aerial Photo Survey)[5];
4. *Imagery and maps from the 2015 aerial survey of the eight main Hawaiian Islands* can be accessed through ArcGIS Story Map[6], and through the State of Hawaii Office of Planning Service Directory[7]; and
5. An *"Identification guide of seaweeds on Japanese tsunami debris"* available on the Kobe University website[8]; and morphological documentation on *"Benthic marine algae on Japanese tsunami marine debris"* accessible through Oregon State University's online library[9] have been prepared to assist the user in detecting JTMD algal species in the eastern North Pacific.

The ADRIFT Science Team considers it essential to share information from the project with the scientific community and the general public on both sides of the Pacific. This has been done not only through publications in peer-reviewed journals, reports, newsletters, and conference presentations, but also through outreach activities such as lectures and seminars for university and grade school students, public events and exhibitions, and numerous media interviews. Two special outreach products highlighting the project's purpose and findings for the general public are: an *ADRIFT Factsheet* – a colorful brochure (in English and in Japanese) distributed in printed form and through the PICES website[10], and an *ADRIFT Videoscribe* – a 4-minute narrated animation posted on YouTube[11].

Cathryn Clarke Murray, Thomas W. Therriault,
Hideaki Maki, Nancy Wallace, James T. Carlton,
and Alexander Bychkov

Royal B.C. Museum

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[1] https://science.sciencemag.org/content/357/6358/1402
[2] http://www.aquaticinvasions.net/2018/issue1.html
[3] https://www.sciencedirect.com/journal/marine-pollution-bulletin/vol/132/suppl/C
[4] http://invasions.si.edu/nemesis/jtmd/index.jsp
[5] http://catalogue.data.gov.bc.ca/dataset/pices-tsunami-debris-aerial-photo-survey-map
[6] http://arcg.is/29tjSqk
[7] http://geodata.hawaii.gov/arcgis/rest/services/SoH_Imagery/Coastal_2015/ImageServer
[8] http://www.research.kobe-u.ac.jp/rcis-kurcis/KURCIS/FieldGuide2017may14LR.pdf
[9] https://ir.library.oregonstate.edu/
[10] https://meetings.pices.int/publications/other/ADRIFT-Factsheet-English.pdf
[11] https://www.youtube.com/watch?v=_OUCLMdyllU&feature=youtu.be


U.S. Navy


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Chapter 1: Introduction

Contributing authors: **Cathryn Clarke Murray[1,*], Thomas W. Therriault[2], Hideaki Maki[3], and Nancy Wallace[4]**

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[4] National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA
[*] Now at Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, British Columbia, Canada

The Great East Japan Earthquake, with magnitude 9.1, struck off the Tohoku coast on March 11, 2011, and created a massive tsunami that impacted more than 10,000 square kilometers of coastline, causing loss of human life, property destruction, and environmental damage. The tsunami washed millions of tons of material into the Pacific Ocean and, within a year, marine debris (termed Japanese Tsunami Marine Debris or JTMD) started arriving on the Pacific coast of North America and the Hawaiian Islands. The ecological and biogeographic significance of this event for the eastern North Pacific became evident when, amazingly, numerous living Japanese coastal species of marine flora and fauna were found on two large docks originating from the port of Misawa (Aomori, Japan), and on an ever increasing number of skiffs, as well as smaller and diversified items from Japan.

While large amounts of marine debris are afloat at sea, researchers rarely know where the debris is from, when it entered the ocean, or how long it took to arrive at its destination. The JTMD study provided the first opportunity in the history of marine science to track a multi-year large-scale (more than 7,000 km) transoceanic rafting of marine life initiating from an exact known source and with an exact known sea-entry time.

What makes JTMD different?[1]

Two questions have consistently been posed throughout the course of this research:

1. How does the modern rafting of marine debris with living organisms differ from eons of "natural rafting"?
2. How does marine debris, and in particular JTMD, differ from other anthropogenic vectors that historically and currently transport species from Japan to North America and Hawaii?

How does the modern rafting of marine debris with living organisms differ from "natural rafting"?

Historical rafting largely consists of biodegradable materials such as trees, tree branches, and root masses. Little is known of this process as it applies to the transport of coastal species from Japan to Hawaii or to North America. There have been no reports in the literature of Western Pacific vegetation arriving with living Japanese species in either region, which suggests that such events, while not impossible, are likely rare. The biodeterioration and decomposition of post-and-beam wood over a 2-year period, as observed in this study, advocates that wood is at risk of destruction during its high seas transit by marine wood-borers such as shipworms. In contrast, marine debris has added to the world's oceans long-lasting, non-biodegradable plastics, fiberglass, and other floating materials which appear to fundamentally differ from historic rafting materials in their at-sea longevity. That Western Pacific species have lasted, to date, for over 5 years drifting in the North Pacific Ocean implies that coastal species are able to survive long-term transoceanic dispersal events, and even grow and reproduce, if provided more permanent rafts, which were lacking historically.

How does marine debris, and in particular JTMD, differ from other anthropogenic vectors that did, do, and will continue to transport species from Japan to North America and Hawaii?

JTMD rafting differs from the modern transport of marine life in both ship fouling and in ballast water in that: (1) JTMD has a much slower at-sea transit speed (1–2 knots/1.9–3.7 km h^{-1}) versus a typical commercial vessel speed (20 knots/37 km h^{-1} or more), thus potentially affecting and impacting the development, adhesion, and retention of fouling communities; (2) JTMD has delivered extensive communities of adult organisms compared to planktonic stages of benthic and fouling species in ballast water; and, (3) JTMD transport typically is a one-way (unidirectional) arrival event, leading to the potential for living communities on debris, landing in shallow water, to have extended periods of time for reproduction and colonization compared to biofouled vessels residing in port for only hours or days thereby providing limited time for colonization. Through this project, we quantified the reach and impacts of JTMD, and compared JTMD as a vector of non-indigenous species to other known invasion vectors, such as ballast water, hull fouling, aquaculture, and ornamental trade.

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[1] This section is taken from Chapter 7 (Carlton et al.) in the present volume.

John Chapman

Identification of objects as Japanese Tsunami Marine Debris[2]

A variety of methods have been employed to distinguish JTMD – that is, objects specifically lost from the Japanese coast on March 11, 2011 – from marine debris in general. Highest confidence in designating items as JTMD was achieved through a combination of evidence as follows:

1. **Formal object identification:** Registration numbers or other numeric identification present on an object, from which data could then be provided to the Japanese Consulate for confirmation.
2. **Known Japanese manufactory:** Unique Japanese manufactory, including buoys, and post-and-beam lumber from Japanese homes and businesses, combined with the absence of a prior history of landings of these objects in North America and Hawaii.
3. **Bioforensics:** Objects bearing a biological "fingerprint" of the northeast coast of Honshu island, particularly of the fauna of the Tohoku region. Thus, items bore a non-random diversity typical of the shores of the Aomori, Iwate, Miyagi, and Fukushima Prefectures. If large numbers of non-tsunami objects were arriving, they would be predicted to have species aboard from a wide range of source regions of the Western Pacific Ocean.
4. **Pulse event timing:** Objects arriving in the predicted "tsunami debris pulse window," commencing in steady and increasing numbers from 2012 on, and characterized by subsequent slowing in item arrivals as the debris field entered its fourth, fifth, and sixth years. If debris items were arriving independently and gradually at a background rate from the Western Pacific, a steady attrition would not be predicted. In turn, prior to 2012, there were no records published in the scientific, historical, or management-policy literature (though marine biology records have been kept on the Pacific coast of North America and in the Hawaiian Islands since the 1850s) of any object landing in the Central or Eastern Pacific with diverse communities of living species from the Western Pacific Ocean. In striking contrast, a consistent novel pattern since 2012 was observed of objects arriving in North America and Hawaii, including many vessels of the exact type and construction known to be lost from Aomori, Iwate, Miyagi, or Fukushima Prefectures, and consistent with modeled debris arrival timing.
5. **Vessels:** Finally, 100% of all objects (vessels or otherwise) intercepted in Hawaii or the Pacific coast of North America since 2012 that are thought to be from Japan and have been traced to their exact origins are solely from Aomori, Iwate, Miyagi, or Fukushima Prefectures. In turn, no losses of vessels (or many other items in large debris fields) have been reported from Japan, other than due to the earthquake and tsunami, since March 2011.

Project overview

The overall goal of this PICES project, funded by the Ministry of the Environment (MoE) of Japan, was to assess and forecast the potential effects of JTMD, especially those related to non-indigenous species (NIS), on ecosystem structure and function, the coastlines, and communities along the Pacific coast of North America and the Hawaii Islands, and to suggest research and management actions to mitigate any impacts. The project, referred to as ADRIFT (**A**ssessing the **D**ebris-**R**elated **I**mpact **F**rom the **T**sunami), spanned three years, from April 15, 2014 to March 31, 2017, and brought together researchers from multiple scientific disciplines from Canada, Japan, and the United States of America (see Chapter 18).

ADRIFT was directed by a Project Science Team (PST), co-chaired by three PICES members: Dr. Hideaki Maki (National Institute for Environmental Studies, Japan), Dr. Thomas Therriault (Department of Fisheries and Oceans, Canada) and Ms. Nancy Wallace (NOAA Office of Response and Restoration, USA). The PST Co-Chairs were responsible for the scientific implementation of the project and annual reporting to MoE and PICES Science Board. They were strongly supported by PICES' first Visiting Scientist, Dr. Cathryn Clarke Murray. Dr. Alexander Bychkov served as the Project Coordinator and was responsible for the management of the fund and for reporting annually on its disposition to MoE and PICES Governing Council.

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[2] This section is taken from Chapter 7 (Carlton et al.) in the present volume.


Hideaki Maki

Participants of the Topic Session on *"The effect of marine debris caused by the Great Japan Tsunami of 2011"* at the 2016 PICES Annual Meeting (November 8–9, 2016, San Diego, USA): Front row, kneeling (from left to right): Nikolai Maximenko, Alexander Bychkov, and Thomas Therriault; standing: Nancy Treneman, Hideaki Maki, Tomoya Kataoka, Yutaka Michida, Gayle Hansen, Shin'ichiro Kako, Atsuchiko Isobe, Kristen Moy, Jonathan Geller, Gregory Ruiz, John Chapman, James Carlton, Sherry Lippiatt, Hiroshi Kawai, Nancy Wallace, Reva Gillman, Naohisa Kanda, Sandra Lindstrom, Taichi Yonezawa, Cathryn Clarke Murray, and Jocelyn Nelson.

ADRIFT focused on three major themes:

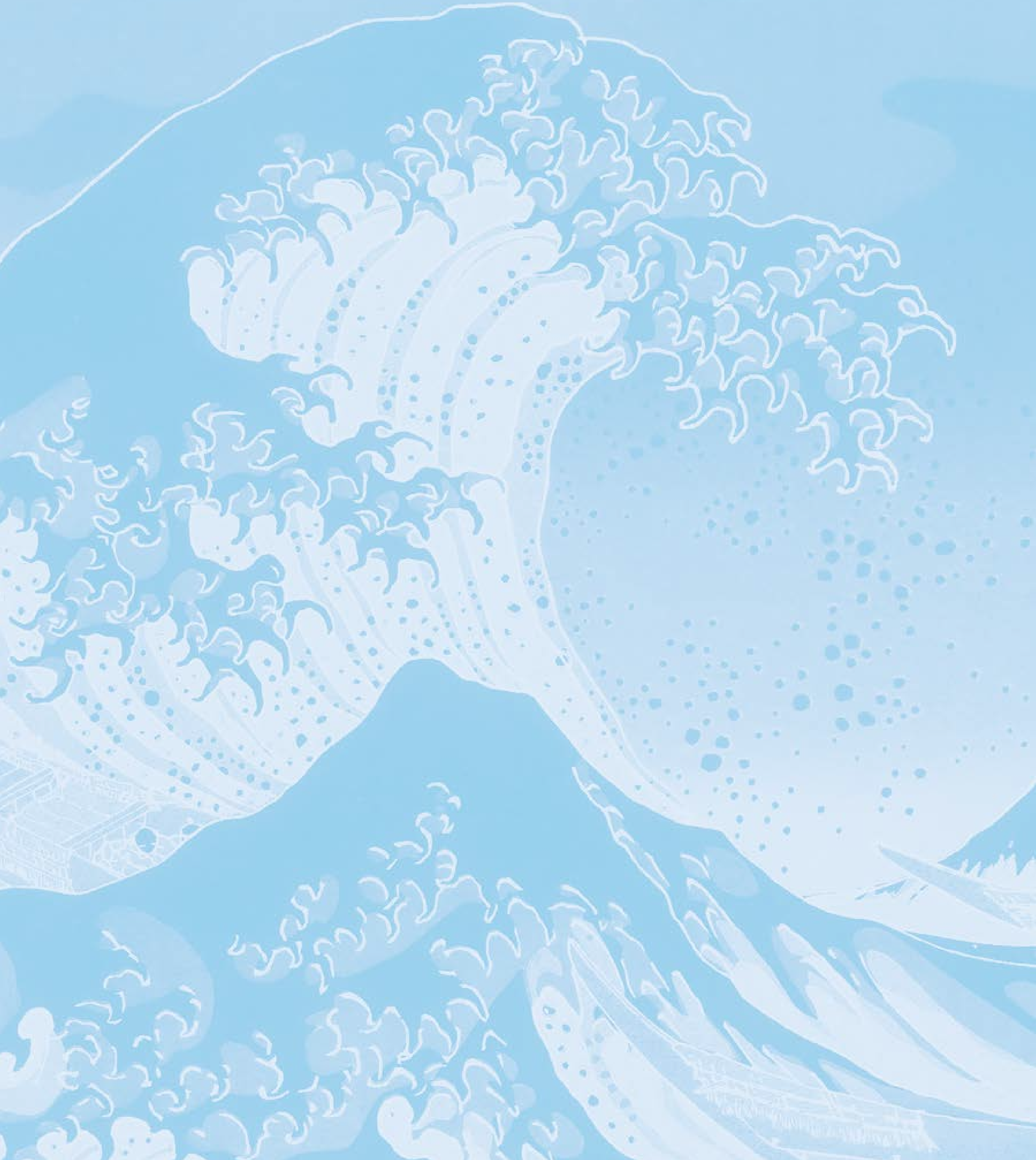
1. Modeling movement of marine debris in the North Pacific to forecast and hindcast JTMD trajectories and landings,
2. Surveillance and monitoring of JTMD landfall and accumulation, and
3. Characterizing and assessing the invasion risk of NIS transported on JTMD to coastal ecosystems.

Information from the project was shared with the scientific community through a Topic Session on "*The effect of marine debris caused by the Great Japan Tsunami of 2011*" at the 2016 PICES Annual Meeting (November 2016, San Diego, USA), an International Symposium on "*Effects of marine debris caused by the Great Japan Tsunami of 2011*" (May 2017, Tokyo, Japan), and a Topic Session on "*The risk of marine debris mega-pulse events: Lessons from the 2011 Great Japan Tsunami*" at the Sixth International Marine Debris Conference (March 2018, San Diego, USA).

This publication, detailing the project's research activities and findings, is divided into six themes: (I) movement of debris – Chapter 2, (II) arrival of debris – Chapters 3 to 6, (III) rafting of Japanese species on JTMD – Chapters 7 to 10, (IV) characteristics of JTMD species – Chapters 11 and 12, (V) detection of invasion – Chapters 13 and 14, and (VI) risk of invasion – Chapters 15 and 16.


NOAA

L-R, top - bottom rows: 1: debris cleanup, Linda Leitch; beach walk, Lightspeed Digital; invertebrates lab, Royal B.C. Museum. 2: wood samples, Nikolai Maximenko; Seal Rock boat, John Chapman; beach walk, Lightspeed Digital; particles, Charles Moore. 3: beach walk debris, Lightspeed Digital; cleanup, Larry Pynn; gooseneck barnacles on debris, Cathryn Clarke Murray; debris sorting, Larry Pynn. 4: beached vessel, Washington Fish and Wildlife; Japanese seastars, Jessica Miller; beach cleanup, John Chapman. 5: examining debris, Lightspeed Digital; examining debris, John Chapman; sawing wood sample, Nancy Treneman; beakfish species, Washington Fish and Wildlife. 6: mussel boat, John Chapman; Japanese green bucket return, Hideaki Maki; tractor towing beached vessel, Cathryn Clarke Murray. 7: hull fouling, Cathryn Clarke Murray; scraping dock, Robin Loznak; beached dock, John Chapman.



NOAA

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THEME I – Movement of Debris

Chapter 2: Modeling oceanographic drift of Japanese Tsunami Marine Debris[1]

Contributing authors: Nikolai Maximenko[1], Amy MacFadyen[2], Masafumi Kamachi[3], and Jan Hafner[1]

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[2] Emergency Response Division, NOAA, Seattle, Washington, USA
[3] Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

Abstract

To model the movement of Japanese Tsunami Marine Debris (JTMD) items and the accompanying environmental conditions that the associated biota would have experienced during the journey, the ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project used three numerical models: the Surface CUrrents from Diagnostic (SCUD) model operated at the International Pacific Research Center (IPRC) of the University of Hawaii, General NOAA Operational Modeling Environment (GNOME) model based on the Navy's HYbrid Coordinate Ocean Mode (HYCOM) Ocean General Circulation Model (OGCM) operated by the National Oceanic and Atmospheric Administration (NOAA), and the MOVE/K-7/SEA-GEARN system operated by the group which includes the Meteorological Research Institute (MRI), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and Japan Aerospace eXploration Agency (JAXA). Model solutions were validated and scaled using available observational data, and new methods were developed to facilitate the interdisciplinary research. Sensitivity of JTMD fluxes on the Pacific North American and Hawaiian shorelines to the distribution of sources along the east coast of Japan, affected by the tsunami, was shown in numerical experiments.

Model experiments, providing the overall description of the paths and fates of different types of JTMD, demonstrated that, consistent with observational reports, the ecoregions on the Pacific coast of North America that were most affected by JTMD extended from California to Alaska and also included Hawaii. The majority of high-windage items were directed by the wind to northern areas, while many low-windage items recirculated into the Subtropical Gyre. A significant fraction of the latter is still adrift in the North Pacific. The particular case of JTMD small boats demonstrated excellent correspondence between reports from North America and model solutions, allowing the estimate that originally about 1,000 boats were washed into the ocean by the tsunami, of which 100 are projected to still be floating in 2018 (Maximenko et al., 2018).

Model results, combined with statistics of satellite temperature observations, were used to demonstrate that conditions along the Pacific coast of North America and in Hawaii were within the range of those along the eastern shores of Japan. New methods and approaches developed by the ADRIFT project's modeling team allowed us to derive trajectories of the most significant JTMD items. The methods were based on a probabilistic approach, interpreting tracer concentration as a probability density function of a single particle. This permitted useful assessments even in cases where important information about the source, destination, or windage of items was missing or inaccurate. This technique has been used to calculate probable trajectories of individual JTMD items as well as probable oceanographic conditions (temperature, salinity, sea state, chlorophyll, etc.) along the JTMD paths, thereby facilitating assessment of possible survival of coastal species during their trans-Pacific travel.

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[1] A reduced version of this chapter first appeared in PICES Press Vol. 23, No. 2, 2015. A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 5-25.

Introduction

The power of numerical modeling is in its capability to generalize previous experience and apply it to new tasks. Over recent decades, ocean general circulation models (OGCMs) and ocean observing systems went through critical enhancements so that many applications have been developed (e.g., for oil spill response and for search and rescue). However, the Great Japan Tsunami of 2011 generated an unprecedented amount of debris whose paths, fate and impacts became a challenge for oceanography and for society.

The purpose of the modeling component of the ADRIFT project included:

- Use numerical models to improve our understanding of the paths, patterns, timelines and fate of JTMD,
- Calibrate models against observations and help to convert patchy observations into a coherent picture,
- Whenever possible, help to obtain integral estimates of JTMD impacts,
- Support interdisciplinary research, such as vector risk assessment.

The research objectives were to:

1. Develop models that adequately simulate motion of JTMD,
2. Develop techniques that allow us to validate/calibrate the models and derive integral characteristics of JTMD, and
3. Support biological studies by providing model assessments on the feasibility of trans-Pacific travel of coastal species from various ecoregions in Japan.

Methods

To address the questions formulated in the ADRIFT project, the modeling team developed a set of new methods and enhanced existing techniques. The accuracy of the modeling results was verified through their comparison with available observations and in sensitivity studies. Numerical experiments were conducted using three different models and different setups.

SCUD model

The SCUD (Surface CUrrents from Diagnostic) model was developed at the International Pacific Research Center (IPRC), University of Hawaii to obtain high-resolution maps of ocean surface currents, consistent with trajectories of the sparse array of satellite-tracked drifting buoys, drogued at 15 meter depth. The model utilized two satellite data sets: sea level anomaly from altimetry, processed by the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) program and surface wind from QuickSCAT (1999–2009) and Advanced Scatterometer (ASCAT, since 2007) satellites. The model currents were calculated as a combination of mean flow, geostrophic anomalies, and locally-induced Ekman currents. The model coefficients were calibrated using collocated (in time and space) velocities of nearly 18,000 drifting buoys of the Global Drifter Program and satellite observations. The SCUD model produced daily, near-real time, nearly global maps on a ¼-degree grid, distributed through the IPRC servers (Maximenko and Hafner, 2010). The effect of the direct wind force, applied to the part of marine debris object sticking out of water, was described by adding a corresponding fraction of the local wind vector (windage) to the advection by ocean currents. SCUD has been successfully used to describe the global distribution of microplastics (Maximenko, 2009; Maximenko et al., 2012), and model solutions helped to explain historical data (Law et al., 2010; van Sebille et al., 2015) and empirically verify new garbage patches (Eriksen et al., 2013).

MOVE/K-7/SEA-GEARN model

The MOVE/K-7/SEA-GEARN drift/dispersion model was created by a team of scientists from JAMSTEC, Japan Atomic Energy Agency (JAEA), MRI, and JAXA in order to examine the debris positions in the North Pacific as well as its landing sites and dates on the coastlines after the Great East Japan Earthquake and Tsunami that occurred on March 11, 2011. Model simulations that provided velocity products and particle data used in this project included:

- Calculation of ocean currents from March 2011 to August 2013 using a data assimilation model with an eddy-resolving general ocean circulation model (the MOVE system by JMA/MRI),
- Forecasting current and wind fields from September 2013 to May 2016 by an atmosphere–ocean–land coupled data assimilation system (K-7 system by JAMSTEC),
- Calculation of dispersion of marine debris using the above-mentioned current and wind fields with a dispersion model (SEA-GEARN by JAEA).

Analysis of the model experiments and its verification using available observations has been published by Kawamura et al. (2014).

GNOME model

Modeling efforts of the NOAA team focused on producing a "hindcast" model run, which simulates the movement of tsunami debris from March 11, 2011 through the present. The debris was modeled as particles initialized at 8 sites along the Japan coast spanning a distance of approximately 700 km. Trajectories were run within the NOAA model GNOME (General NOAA Operational Model Environment). GNOME is a particle tracking model that was initially developed for predicting trajectories of marine pollutants (primarily floating oil). However, GNOME allows user-specified parameterization of the "windage" drift, making it applicable for predicting trajectories of different types of floating or neutrally buoyant material. GNOME utilizes ocean currents from the Global $^1/_{12}$-degree operational HYCOM from the Naval Research Laboratory (HYCOM, 2016) and ¼-degree global NOAA Blended Sea Winds[2]. Unlike other models, GNOME also accounts for such coastal processes as re-floatation of debris temporarily washed ashore.

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[2] https://www.ncdc.noaa.gov/data-access/marineocean-data/blended-global/blended-sea-winds

Model analysis and comparison

Modeling studies on the ADRIFT project combined very different approaches as particle and tracer simulations. Lagrangian particles provided a natural analogy to individual JTMD items drifting across the ocean. At the same time, particles tended to converge in some areas and disperse from others, resulting in large gaps on basin-wide maps. Also, an extremely large number of particles were required to include effects of stochastic processes or parameters that were not known accurately. Tracer concentration, on the other hand, provides a coherent description of the motion of a large ensemble of JTMD items. Tracer concentration reflected the fact that, while trajectories of individual floating objects are subject to various uncertainties, the motion of the tracer "cloud" is highly deterministic. During the project, we further developed this idea into a new probabilistic technique that utilized a model tracer to study pathways of individual JTMD items. This approach interprets the concentration of the tracer as a probability density function for a discrete particle and, combined with all information available from observations, it allowed us to derive the most probable paths of individual JTMD items.

Whenever possible, we used observational data to verify and scale our models. New methods were developed to compare fragmentary JTMD reports and surveys with model fluxes to the Pacific North American coast and to Hawaii and to compare with model tracer concentration in the open ocean.

Probabilistic methods that combined information about JTMD drift with oceanographic (climatological and real-time) data were also developed to help evaluate the possibility of Japanese coastal species traveling to ecoregions in North America and Hawaii with JTMD.

Results and Discussion

Source information

The tragic Great Japan Tsunami of 2011 was a disaster that devastated many towns and villages and changed the appearance of a significant stretch of the coastline of eastern Honshu. Generation of JTMD was a complex multi-phase process: it started with an inundation of coastal areas with tsunami waves, damage to the structures and later washing into the ocean with retreating waters. Exchange between the ocean and land is very complex and depends not only on the tsunami wave height but also on the ocean and land topography, resilience of buildings and structures, etc. While much of the debris was brought in the ocean, there were also many reports of boats, ships and marine structures brought by the same waves onto the land. We used recent data on the number of homes affected by the tsunami, collected by municipal services, and by the Japanese newspaper, Asahi Shimbun (Hideaki Maki, pers. comm.). Figure 2-1a shows the distribution of reports along the shoreline and reveals that the highest number of affected homes was located between 37.5° and 39.8°N. Our analysis of the overlaps between the two sources of the data confirmed good agreement between them, so for towns where two estimates were available we used an average number. In other regions, municipal and newspaper data were used to complement each other (Figure 2-1b). To convert the discrete source data into a continuous function, a set of parameters was explored using a Gaussian filter (Figure 2-1c). Finally, we selected the source distribution function (black line in Figure 2-1c) because it contains a single peak without excessive smoothing. Simulations with this source function replaced the early model experiments using homogeneous or discrete sources of debris. Although this adjustment did not change the main conclusions of our study, some details of model fluxes on the Pacific North American and Hawaiian coastlines were sensitive to the spatial distribution of sources.

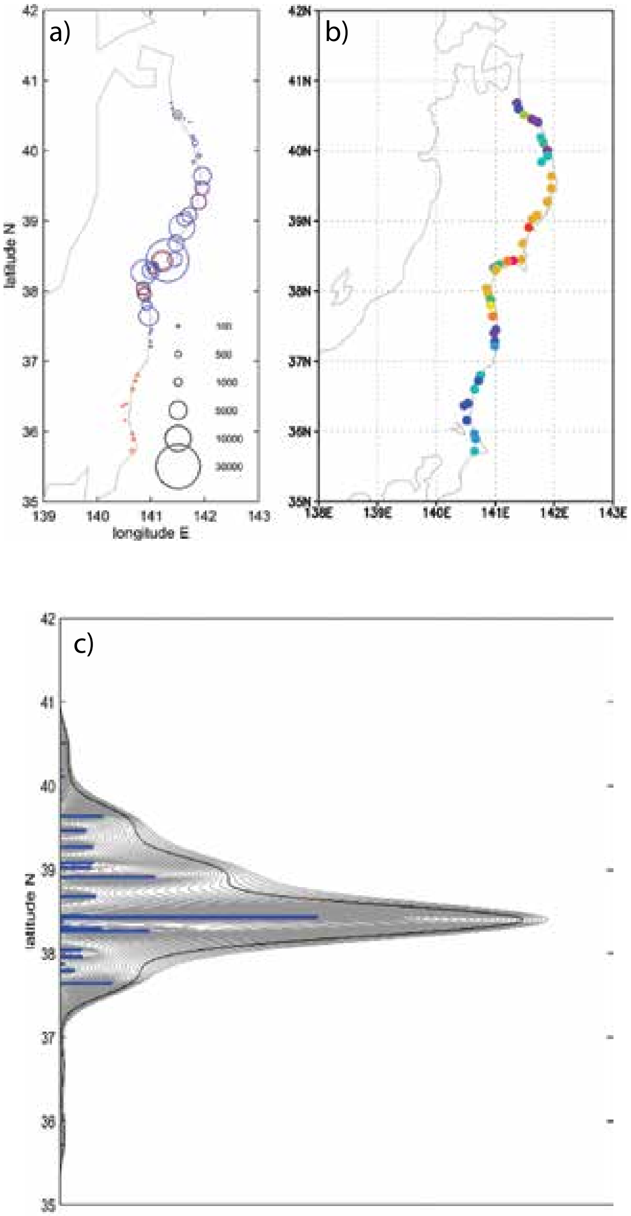


Figure 2-1. (a) Number of affected homes, reported by municipal sources (blue) and Asahi Shimbun (red), (b) composite data distribution, (c) "source function" of JTMD calculated with a variety of filters and used to initiate model simulations.

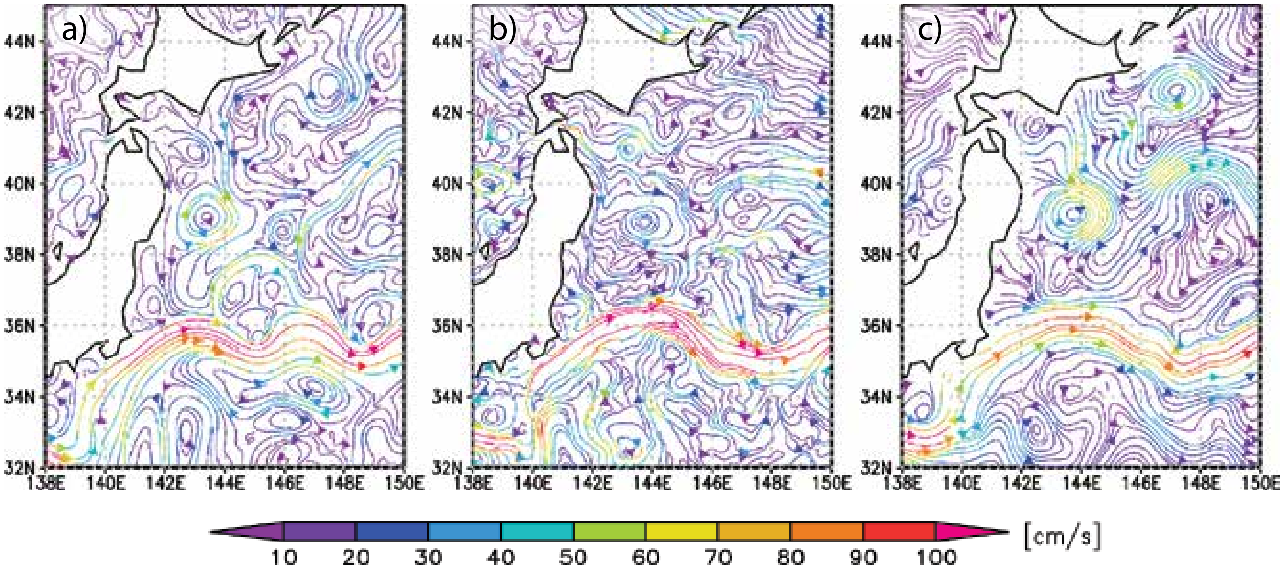


Figure 2-2. Streamlines of surface currents in (a) MOVE/K-7/SEA-GEARN, (b) HYCOM, and (c) SCUD models for March 11, 2011. Colors represent current speed and units are cm/s.

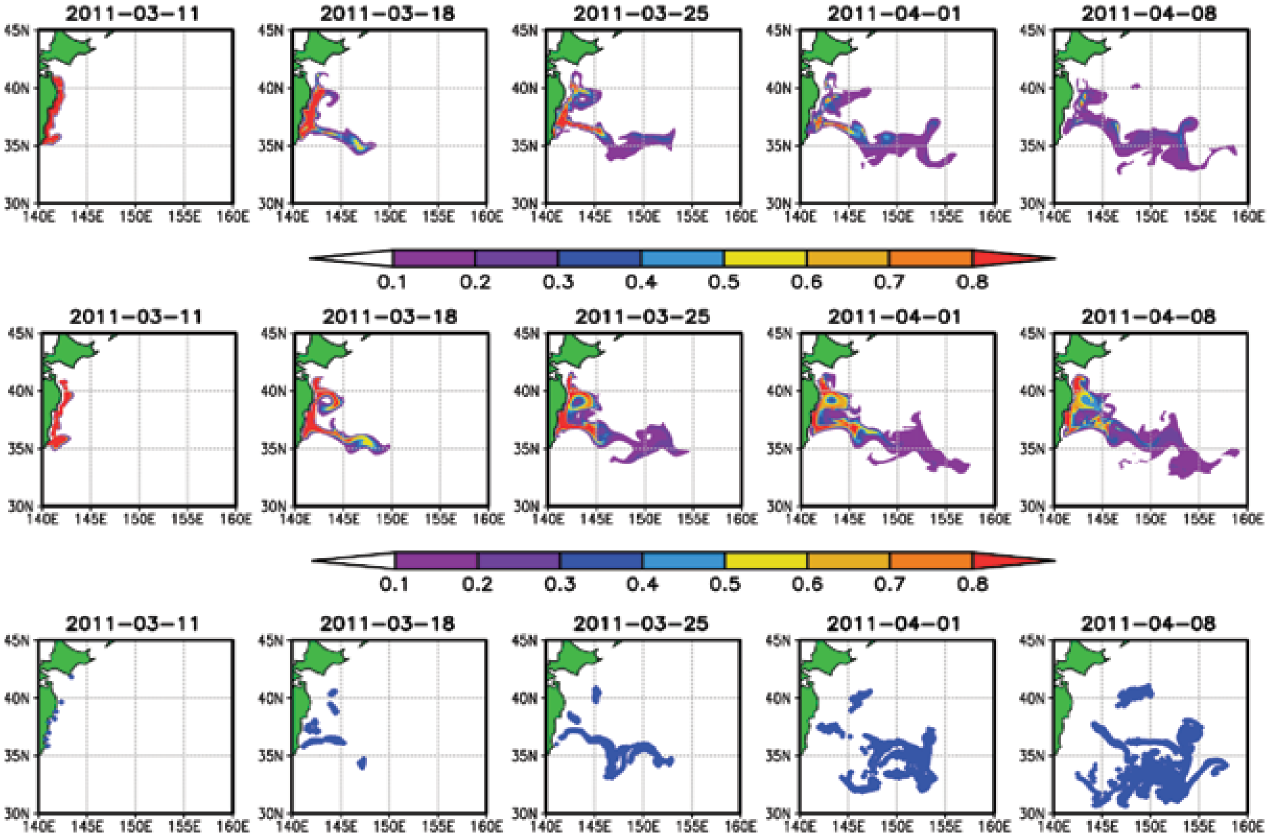


Figure 2-3. Tracer concentration for SCUD (top row), MOVE/K-7/SEA-GEARN (middle row) and particle locations in GNOME (bottom) models for windage parameter 1.5% on March 11, 2011 and 1, 2, 3, and 4 weeks later.

Initial drift from Japan

The structure of ocean currents east of Japan is very complex and characterized by several very strong jets and eddies that determined the initial evolution of the JTMD field before it entered the open ocean. Our analysis of model currents on the day of the tsunami confirmed that most important features were adequately represented in all three models (Figure 2-2) and included: the Kuroshio taking an offshore path south of Honshu, the Kuroshio Extension with a well-developed first meander around 143°E, the subpolar front around 40°N, and a very strong anticyclonic eddy centered approximately at 39°N, 143.5°E. The latter eddy may have played a very important role in the JTMD drift in March 2011. Frequently, there is a branch of the Oyashio Current that flows southward along the east coast of Honshu, but the eddy interrupted this current and pulled JTMD offshore. This process was clearly visible in model simulations illustrated by Figure 2-3.

Particularly good correspondence in initial drift patterns was obtained between the SCUD and MOVE/K-7/SEA-GEARN simulations (Figure 2-3). The northern portion of JTMD was swirling around the eddy center while the southern flank of the JTMD was quickly picked up by the Kuroshio Extension and advected east. This structure agreed well with reports from the Japan Coast Guard who reported a March 20–21, 2011 smaller off-shore extent of the debris field between 37° and 38°N than north and south of these latitudes. Particle simulations with GNOME were difficult to compare with tracers in other models. A model source from 8 point locations produced artificial "blobs" that persisted for at least a month (Figure 2-3 bottom). Also, the GNOME particles demonstrated stronger dispersion in the north–south direction than SCUD or MOVE/K-7/SEA-GEARN.

High-resolution in coastal areas

High model resolution is important for adequate simulations of debris drift in coastal areas, where dynamical scales are commonly smaller than in the open ocean. It was particularly critical for numerical experiments around the Hawaiian Islands. The original model grid of SCUD was a ¼-degree, corresponding to resolution of satellite altimetry and wind data. This grid did not adequately resolve the straits between most of the islands and resulted in the conversion of the chain of islands into a 600-km-long barrier (Figure 2-4a). Model solution in this configuration had a strong tracer gradient between the windward (northeastern) and leeward (southwestern) regions. Originally, to mitigate this problem we interpolated current data over the land. In this configuration (Figure 2-4b), debris flux on the islands was calculated using density of the tracer, velocity of the current and geometry of individual islands. Finally, we improved the model by blending SCUD in the coastal areas with the 10-km HYCOM model data (Figure 2-4c). The latter were unbiased using offshore model inter-comparison and blended as follows: (1) the new model grid is a 10-km HYCOM grid, (2) data > 200 km from shore are interpolated SCUD data, (3) data < 100 km from shore are unbiased HYCOM data, and (4) 100–200 km was a transition zone between the models. The new model (Figure 2-4c) had fully open straits and allowed the full complexity of JTMD motion around the islands. Unfortunately, this does not guarantee that the full complexity of the coastal dynamics was actually captured by the modern model.

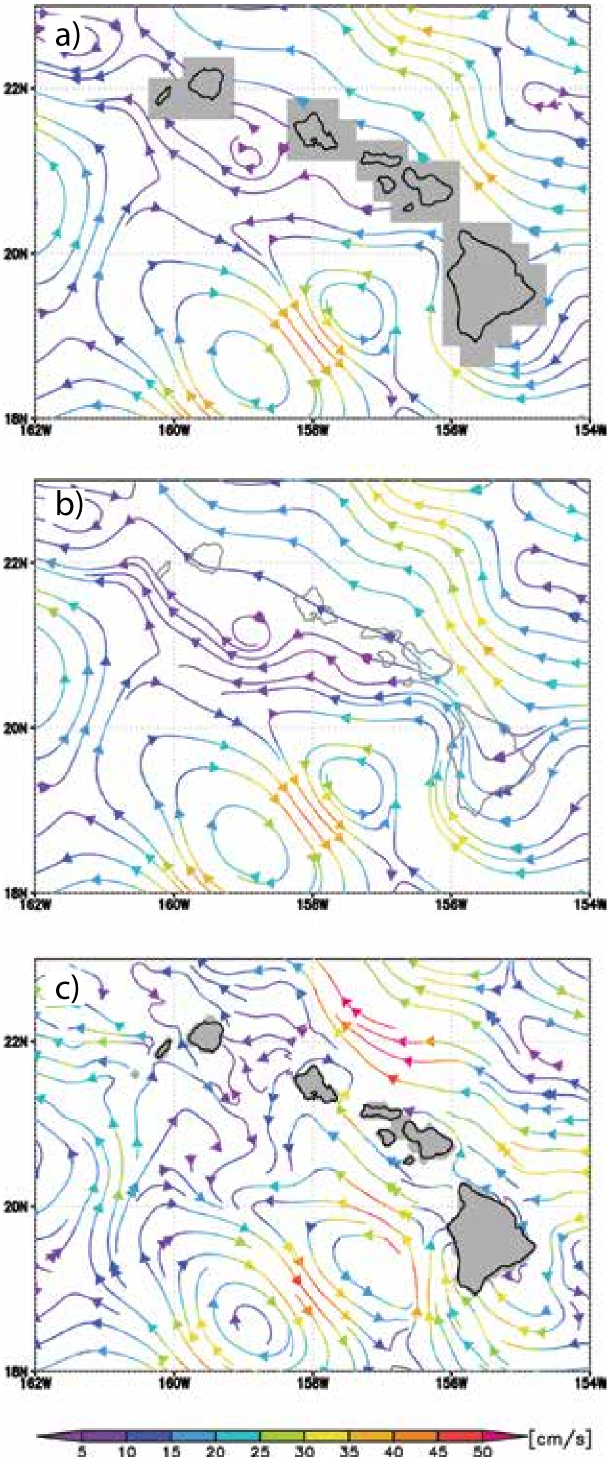


Figure 2-4. Streamlines of surface currents around Hawaii for March 11, 2011 in (a) the original ¼-degree SCUD model (gray shows model land mask), (b) SCUD model interpolated over the Hawaiian Islands, and (c) SCUD model blended with HYCOM data on a 10-km grid. Colors represent current speed and units are cm/s.

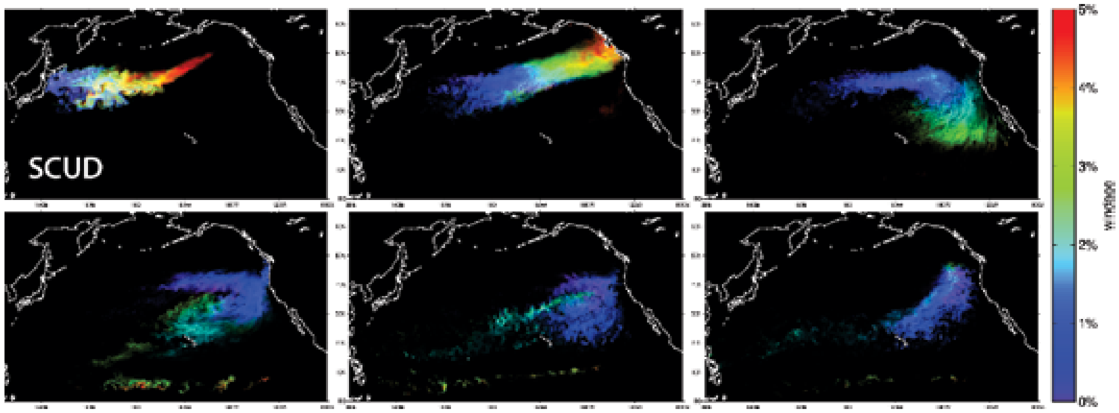


Figure 2-5. Evolution of JTMD tracer in the SCUD model simulations. Colors indicate windage of the debris. Top left to right right: September 1, 2011, March 1, 2012, and September 1, 2012; bottom left to right: March 1, 2013, September 1, 2013, and March 1, 2014.

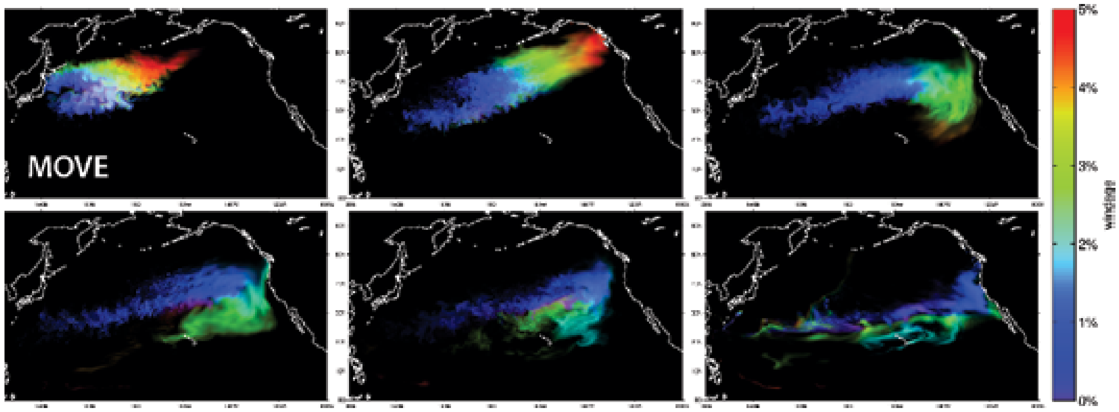


Figure 2-6. Evolution of JTMD tracer in the MOVE/K-7/SEA-GEARN model simulations. Colors indicate windage of the debris. Top left to right: September 1, 2011, March 1, 2012, and September 1; bottom left to right: 2012, March 1, 2013, September 1, 2013, and March 1, 2014.

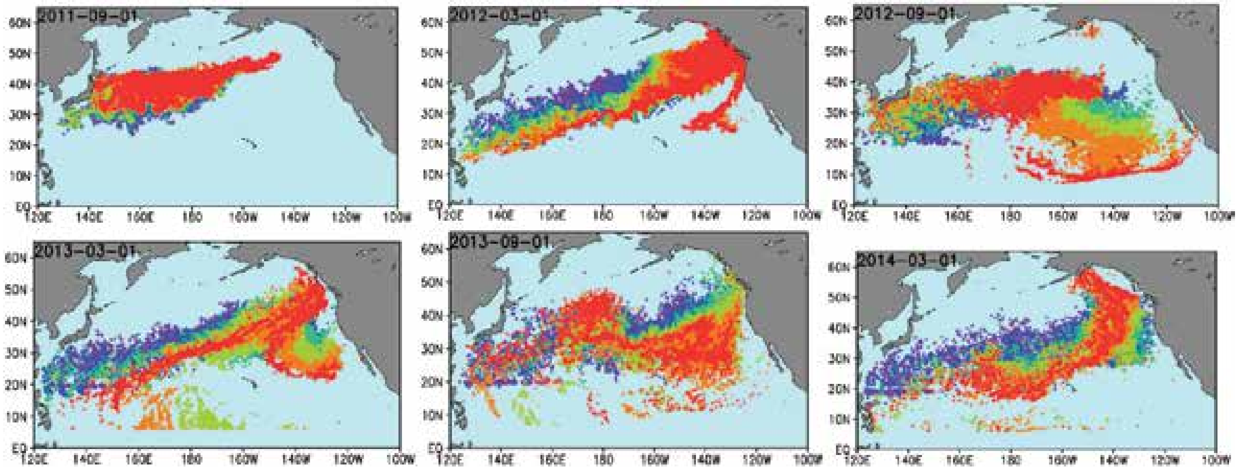


Figure 2-7. Evolution of particle locations in the GNOME model simulations. Colors indicate particle windages according to the color scales of Figures 2-5 and 2-6. High windages are plotted on top of lower windages. Top left to right: September 1, 2011, March 1, 2012, and September 1, 2012; bottom left to right: March 1, 2013, September 1, 2013, and March 1, 2014.

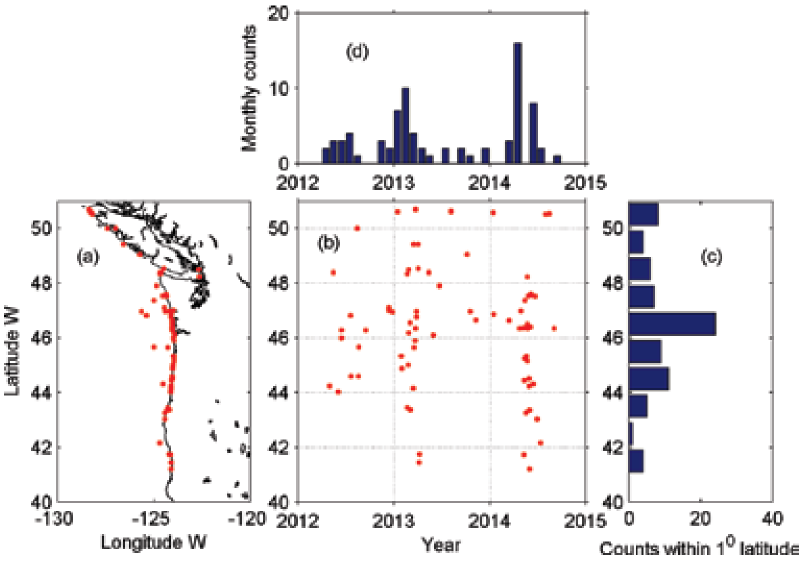


Figure 2-8. Reports of JTMD boats from the U.S./Canada coastline between 40° and 51°N. (a) Location of reports relative to the shoreline, (b) latitude-time diagram, (c) number of reports in 1-degree latitude bins, and (d) monthly number of reports.

Multi-windage modeling based on particle/tracer simulations

Ocean models describe the motion of water parcels. "Windage" is a parameter that characterizes drift of an object relative to the water. Usually, this drift is due to the direct force of the wind and is assumed to be in the direction of the wind and at speed proportional to the wind speed. Note that because wind-driven surface currents have the most complex dynamics and their estimates vary significantly between different models, the latter may need to use different windage values to simulate the drift of the same object. Figures 2-5 to 2-7 show the results of ocean-scale JTMD modeling with the three ADRIFT project models. To address the wide range of JTMD types, all models were run with windage ranging from 0% to 5%. The SCUD (Figure 2-5) and MOVE/K-7/SEA-GEARN (Figure 2-6) models were used to calculate tracer density evolution and GNOME (Figure 2-7) operated with a large number of particles.

Even without further analysis, Figures 2-5 to 2-7 provide an important conceptual description of the drift of JTMD, its pattern, pathways, and fate. All models agree that in the first months after the tsunami, JTMD was sorted according to its windage. High windage tracer and particles moved faster and reached the Pacific North American coast in less than 12 months, when a big fraction washed ashore. In 2012, medium-windage debris recirculated into the eastern Subtropical Gyre and some ended on the Hawaiian Islands. By 2014, most of the tracer was concentrated in the gyre.

Comparison also revealed significant differences between the models. For example, SCUD suggested that the primary residence site of low-windage JTMD was in the eastern Subtropical Gyre, known as a "garbage patch", where concentration of microplastics is known to be high (e.g., van Sebille et al., 2015). At the same time, the MOVE/K-7/SEA-GEARN and GNOME models suggested a broader east–west distribution of JTMD. This discrepancy can be partly explained by the fact that effective windages in the SCUD were higher than in the other two models. Also, after August 31, 2013 the MOVE/K-7/SEA-GEARN model switched into a forecast mode that resulted in some loss of accuracy, especially in the eastern North Pacific where model resolution was degraded to a ½-degree.

Model comparison with observational reports in North America

Overall, observations of marine debris are very sparse making quantitative comparison with the models difficult. Most debris items were hard to discriminate from general debris that was not associated with the tsunami. Reports of tsunami debris boats from the Pacific North American coast were unique in a sense that (1) there was a high probability of them being noticed and reported and (2) many of them could be traced back to the tsunami area and in some cases to the owner in Japan using identification codes. Geographical distribution of North American reports is shown in Figure 2-8a, and by 2015 they could be grouped in three temporal peaks (Figure 2-8b,d). Remarkably, during each peak, reports were received almost synchronously from the full stretch of the shoreline, indicating that the flux of JTMD boats was controlled by relatively large-scale dynamics of the ocean and atmosphere that made the investigation insensitive to many poorly known factors at the nearshore scale.

Direct comparison of observational reports with the models included several steps, as described by Maximenko et al. (2015). First, model fluxes on the chosen part of the shoreline were calculated (Figure 2-9). Then observational reports were filtered to produce a continuous timeline ("Data" in Figure 2-10), and the same filter was applied to the model fluxes. Finally, windages (or combinations of windages) were identified, for which model–observation comparison provided the best correspondence. The SCUD solution for 1.6% windage (blue line in Figure 2-10) contained three main peaks and one secondary peak with time and amplitudes close to the observed timeline. Optimal windages for MOVE/K7/SEA-GEARN (red line in Figure 2-10) and GNOME (green line in Figure 2-10) were somewhat higher: between 2.5 and 3.5%. The former model (red line) correctly simulated the first but missed the second peak and lost the accuracy after switching to the "forecast" mode. The GNOME solution contained all three main peaks but the first peak led

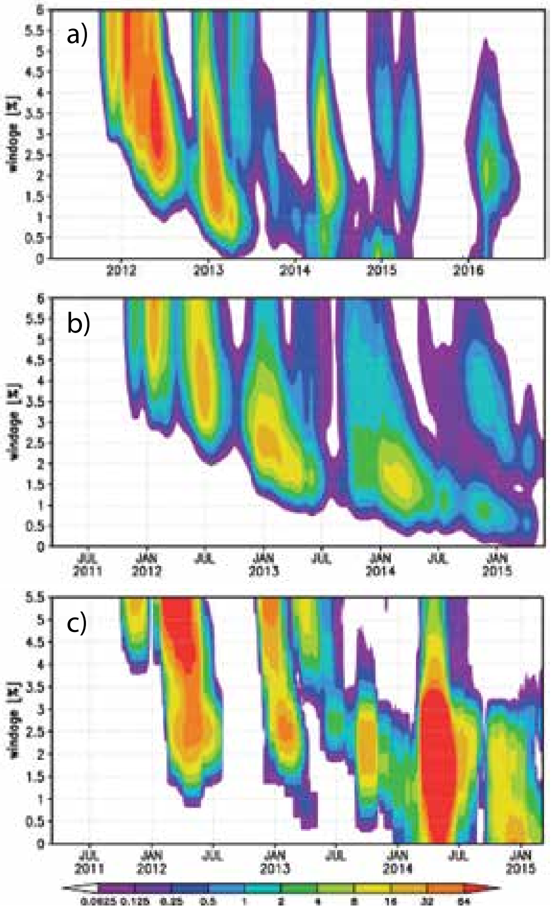


Figure 2-9. Model fluxes timelines on the Pacific North American coast (40°–51°N) for different windages, calculated from (a) SCUD, (b) MOVE/K-7/SEA-GEARN, and (c) GNOME. Units are conventional and differ between the panels.

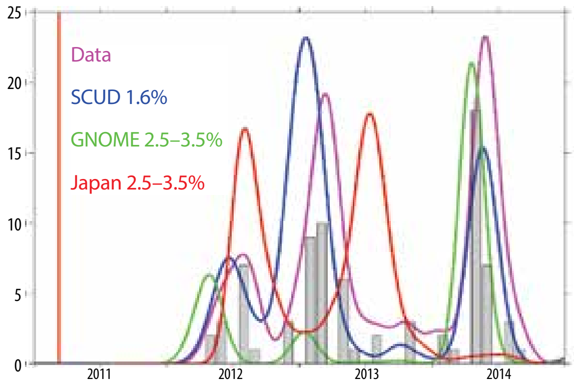


Figure 2-10. Monthly counts of boats on the U.S./Canada west coast (gray bars) and low-pass filtered timelines of boat fluxes in observations (magenta) and model experiments with different windages: 1.6% for SCUD (blue) and 2.5–3.5% averages for GNOME (green) and MOVE-K7/SEA-GEARN (red). Vertical red line marks March 11, 2011. Units on the *y*-axis are boat counts for monthly reports and conventional model units for other timelines.

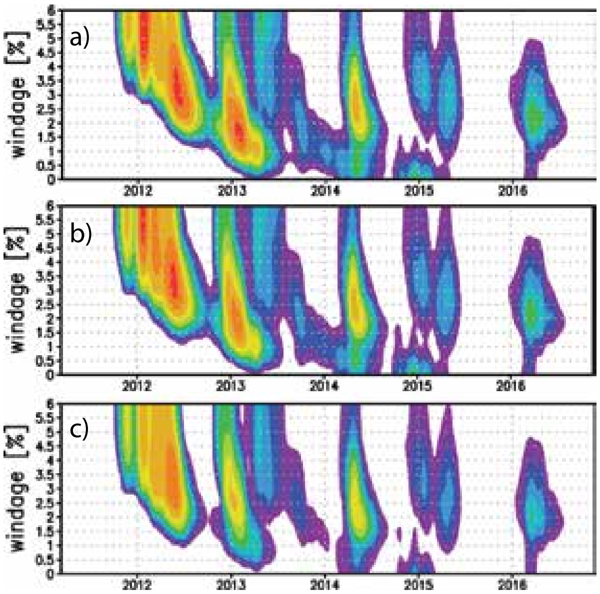


Figure 2-11. Sensitivity of fluxes to the latitude of source (37.5°–39.5°N). Fluxes on the North American coastline in the SCUD simulations with sources of various windage debris located in the (a) northern, (b) central, and (c) southern sectors of the east coast of Honshu affected by the Great Japan Tsunami of 2011. Units are conventional.

observations by 3 to 4 months, and the magnitude of the second peak was severely underestimated. Low magnitude of the second peak in MOVE/K7/SEA-GEARN and GNOME may have been due to the "westward" bias in their solutions seen in Figures 2-6 and 2-7. A high proportion of the model tracer circulated around the large gyre in 2013–2014 before returning to the Eastern Pacific. In contrast, the majority of the tracer in the SCUD model after 2013 resided in the eastern convergence, close to North America.

Scaled and projected back to the start point, the SCUD model estimated 1,000 initial floating boats in March 2011. This does not contradict other estimates. On November 16, 2011, the Japan Coast Guard detected 506 skiffs/vessels drifting off the devastated shoreline (MLIT, 2011). The Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan estimated the total number of fishing skiffs/vessels that were lost or crushed by the tsunami to be 18,936 (MAFF, 2011), but how many of these vessels drifted away remains unknown. The Ministry of the Environment (MoE) of Japan estimated that the total amount of skiffs and vessels that became JTMD was about 102,000 tons, but the total tonnage of skiffs/vessels that floated away was only 1,000 tons (MoE, 2011). The scaled SCUD solution estimated that less than 10% of the tracer washed ashore annually and suggested that more than 70% of JTMD with windage close to 1.6% (equivalent to 400-700 boats) was still floating at the end of 2014. By 2018, this number was reduced to 100 boats that could continue to arrive on various shores in the future years.

In addition to large-scale biases, fluxes in Figure 2-10 may differ in different models due to somewhat different distribution of sources. A simple illustration can be found in Figure 2-11 that compares the JTMD fluxes in the SCUD model coming to the Pacific North American coast from sources located in three different regions on the east coast of Japan. Although the main peaks are represented in all model runs, the amount of tracer coming from the northern and central areas of Japan is markedly higher than from the southern segment. According to Figure 2-1, the "central" region of Figure 2-11b corresponds to the area with the most affected homes. However, it is not clear whether there is a strong correlation between the number of homes and number of JTMD boats.

Model comparison with observational reports from Hawaii

Another area where JTMD has been relatively well documented are the main Hawaiian Islands. Located in the central Subtropical Gyre, they receive lower-windage marine debris than typical for the Pacific North American coast. With a relatively short shoreline and relatively high population density (say, compared to Alaska), many sites on the Hawaiian Islands have very complex terrain and are hard to reach. With a few rare exceptions, debris hot spots, collecting large amounts of litter, are very localized and driven by a strong local dynamics of waves, currents and wind (see Chapter 6). Unlike the Pacific North American coast, where waves of debris have seasonal time scales and high probability to interact with a receiving beach, in Hawaii there is a high probability for debris to bypass the land, floating around and between islands to return back to the open ocean. As a result, peaks in debris arrival timelines are less pronounced (Figure 2-12).

In addition, the sites in Hawaii monitored by volunteer cleanup groups cover only selected parts of the islands, so that some phases of debris flux were observed better than others. For example, almost all JTMD boat reports from Kauai came from the eastern sector (Figure 2-12d) which is actively monitored by the Surfrider Foundation Chapter led by Dr. Carl Berg. It is not clear if other shores did not receive boats or if the boats were not reported. The timeline of the monthly number of boat reports contains hints on several peaks (Figure 2-12) but they were much less pronounced than those seen in North America (Figure 2-8). Some peaks appeared synchronously on several islands but others did not.

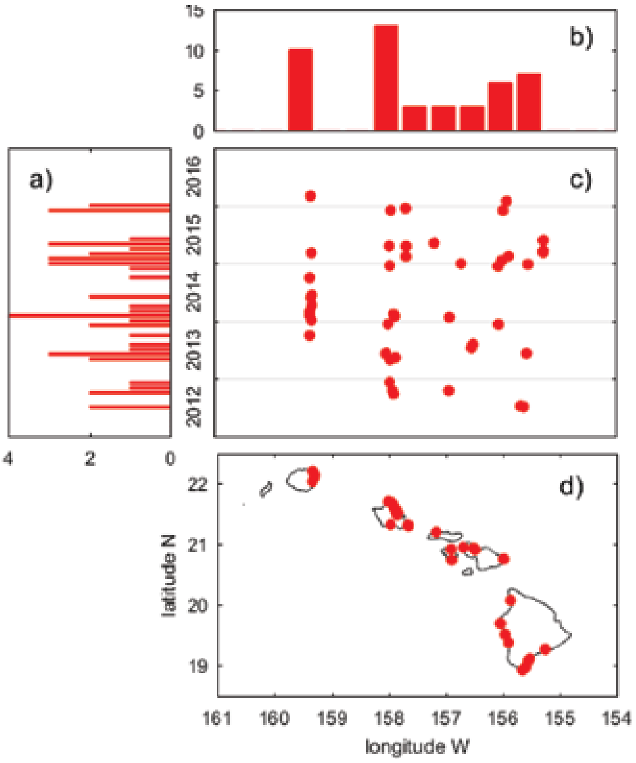


Figure 2-12. Reports of 45 JTMD boats from the main Hawaiian Islands coastline. (a) Monthly number of reports, (b) number of reports in ½-degree longitude bins, (c) longitude-time diagram, and (d) location of reports relative to the shoreline.

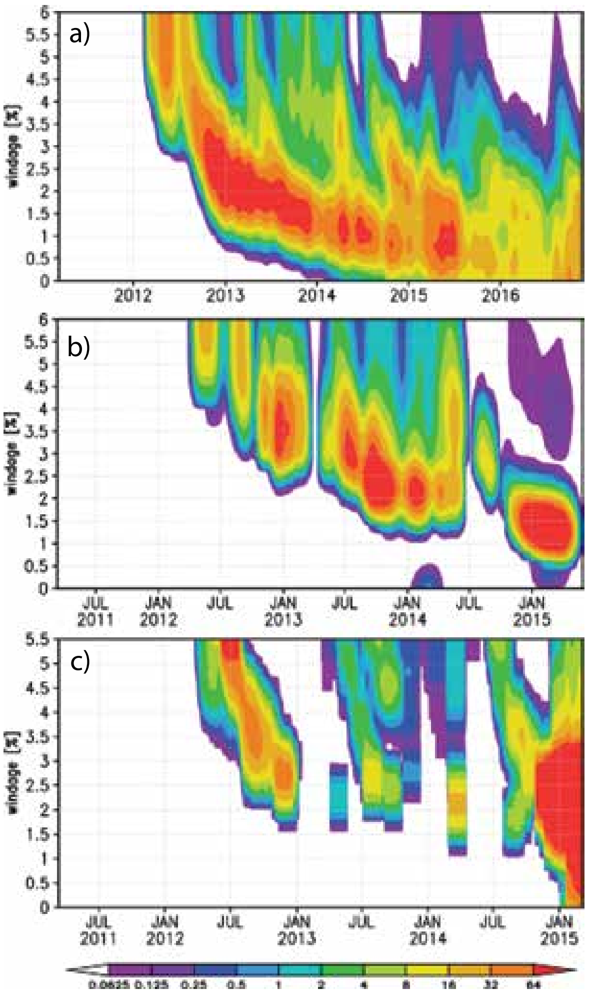


Figure 2-13. Model fluxes timelines on the Hawaiian coast for different windages, calculated from (a) SCUD, (b) MOVE/K-7/SEA-GEARN, and (c) GNOME. Units are conventional and differ between the panels.

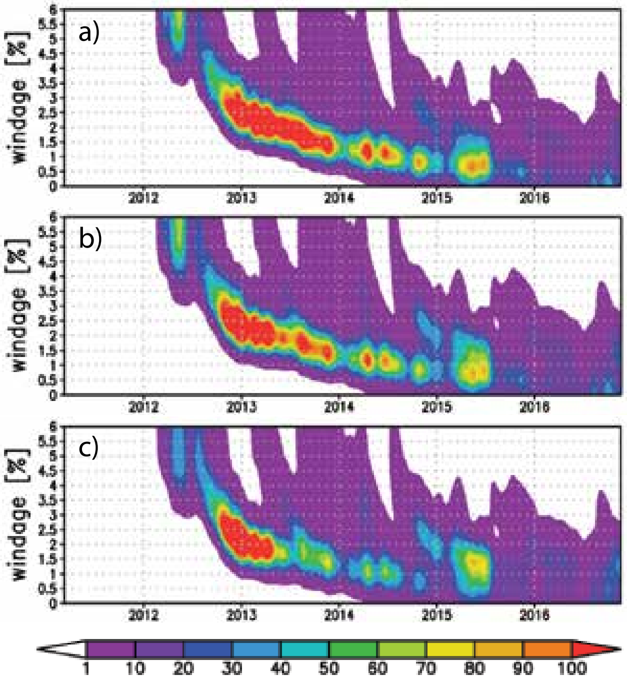


Figure 2-14. Sensitivity of debris fluxes to the latitude of source (35.5°–37°N). Fluxes on the Hawaiian coastline in the SCUD simulations with sources of various windages located in the (a) northern, (b) central, and (c) southern sectors of the east coast of Honshu, affected by the Great Japan Tsunami of 2011. Units are conventional.

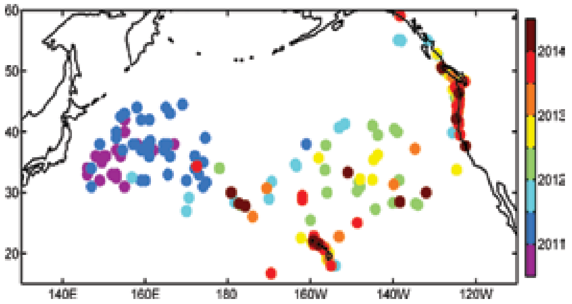


Figure 2-15. Reported locations of boats/skiffs/ships (filled circles) and times (colors) of the reports. Color bar spans January 2011 to December 2014 and labeled ticks mark central moments of the years.

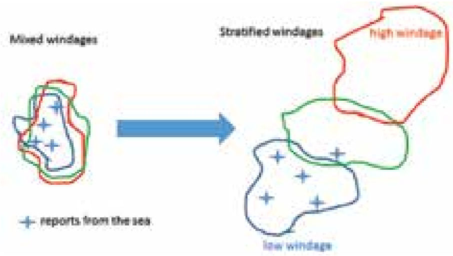


Figure 2-16. Illustration of the method of optimal windage estimate by subsampling model solution at locations/time of marine debris reports.

The complexity of the island dynamics is illustrated by the significant differences between the fluxes in the three ADRIFT project models (Figure 2-13). At the time of this report, no satisfactory correspondence was found between observations and models. Each of the models produced peaks which coincided with some peaks in the observational timeline, but they strongly disagreed with observations during other periods.

Similarly to Pacific North America, fluxes in Hawaii demonstrated dependence on the source location in the north, center or south of the area affected by the tsunami (Figure 2-14). Especially peculiar is the conclusion, supported by Figure 2-14a, that Hawaii is more connected to (i.e., receives more tracer from) the north of Honshu. The explanation of this fact can be found by considering the pathways of JTMD shown in Figures 2-5 to 2-7. One can see that model does not predict movement of debris from Japan to Hawaii directly but recirculates from the northeast. This recirculation is more feasible for tracer coming from northern sources, while tracer from the southern regions gets more easily trapped in the subtropical convergence.

Model comparison with at-sea observational reports

In addition to reports from the shoreline, a large number of observations were collected at sea. This valuable information was not readily available for model validation because it was tremendously sparse and biased towards reports from shipping lanes. Figure 2-15 illustrates the distribution of boat reports in space (filled circles) and time (colors). Careful analysis revealed that the pattern of the dots reflected the pattern of ship lanes and search campaigns rather than the pattern of drifting JTMD boats. Also, there were no reports from the areas where JTMD was not present. Such negative reports would be very helpful in outlining the pattern of JTMD clusters but, unfortunately, they were not recorded. However, we noticed that even this limited dataset reflected systematic drift of the JTMD boats from west to east (change in color from purple and blue in the west to green, yellow and red in the east) and developed a new technique allowing the evaluation of model performance by subsampling model solutions at locations and times of the JTMD boat reports.

The idea of the method illustrated in Figure 2-16 was that the greater the overlap between the "clouds" of the model tracer and reported JTMD items, the higher is the value of the model tracer concentration retrieved at the JTMD item location. This technique can be used to compare performance of different models or performance of the same model under different settings (e.g., windage of the tracer).

The evolution of a tracer cloud in the SCUD and MOVE/K7/SEA-GEARN models after release east of Japan was simulated for 61 values of windage parameter ranging between 0 and 6%, with concentration normalized by the volume of the source (Figure 2-17). The GNOME model was used to release about 40,000 particles for each of 23 windage values ranging between 0 and 5.5%. Distance to the nearest model particle was calculated from each boat report and concentration was estimated as one particle per an area of the circle of radius twice the distance. Particle concentration was then normalized by the number of released particles.

Two models (SCUD and MOVE/K7/SEA-GEARN) performed equally well, while their comparison with the particle-based GNOME model was difficult (Figure 2-17). Optimal windage values were estimated at 1.4% for SCUD and 3% for GNOME and were in excellent agreement with similar estimates in Figure 2-10. At the same time, MOVE/K7/SEA-GEARN performed best at 0.5 to 2.5% windages that was somewhat lower than in Figure 2-10 – the reason for such discrepancy is currently not known.

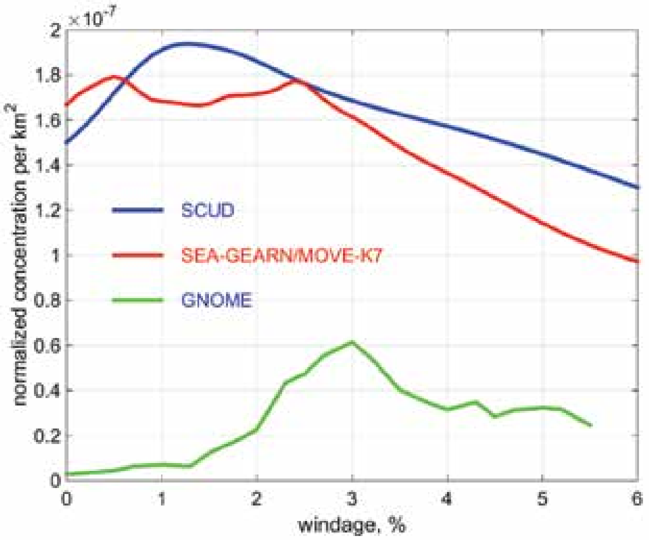


Figure 2-17. Mean tracer concentrations for SCUD (blue), MOVE/K7/SEA-GEARN (red) and GNOME (green) for different windage values averaged over locations and times of boat reports shown in Figure 2-15 and model solutions shown in Figures 2-5 to 2-7.

Patterns on shore

One of most challenging questions on the models was whether they could adequately reproduce coastal "hot spots", i.e., locations that collected more debris than other areas. This was not easy to answer as observational data were not available on the model scale. Comparison between models and JTMD reports was difficult because information on the coastline accessible to the debris floating near the shore (as a sandy beach versus a vertical cliff) as well as availability of observers who would notice and properly report the JTMD, was largely unknown and could not be included in the models. In some cases (such as in Figure 2-10) averaging over a larger domain helps to reduce the effects of unaccounted factors. Distribution of the model tracer at 1.6% windage shown in Figure 2-18b had a maximum between 43° and 48°N that was in good agreement with the distribution of JTMD boat reports shown in Figure 2-8c. Field data demonstrated a peak in debris near 46°N that was not captured in the model. This may indicate that ocean dynamics (such as possible bifurcation of the North Pacific current) was not relevant to the observed spike, which was likely due to a larger (compared to other areas) number of visitors and scientists to the shoreline from nearby population centers, such as Portland, Oregon.

In Hawaii, the distribution of reports (Figure 2-12d) was even more complex and agreement with the models varied between islands and windages. For example, at 3% windage, model tracer ended on the eastern side of Kauai island more frequently than on the western side (Figure 2-19). This was in good agreement with boat reports as well as with the case of the windward (northeast-facing) shore of Oahu. At the same time, many reports from Big Island (Island of Hawaii) came from the western side – area of Kailua-Kona – where the model did not produce much flux.

These examples suggest that more studies are required in the future to help understand the effects of the coastal dynamics and patterns on observations and to scale it for comparison with ocean model simulations.

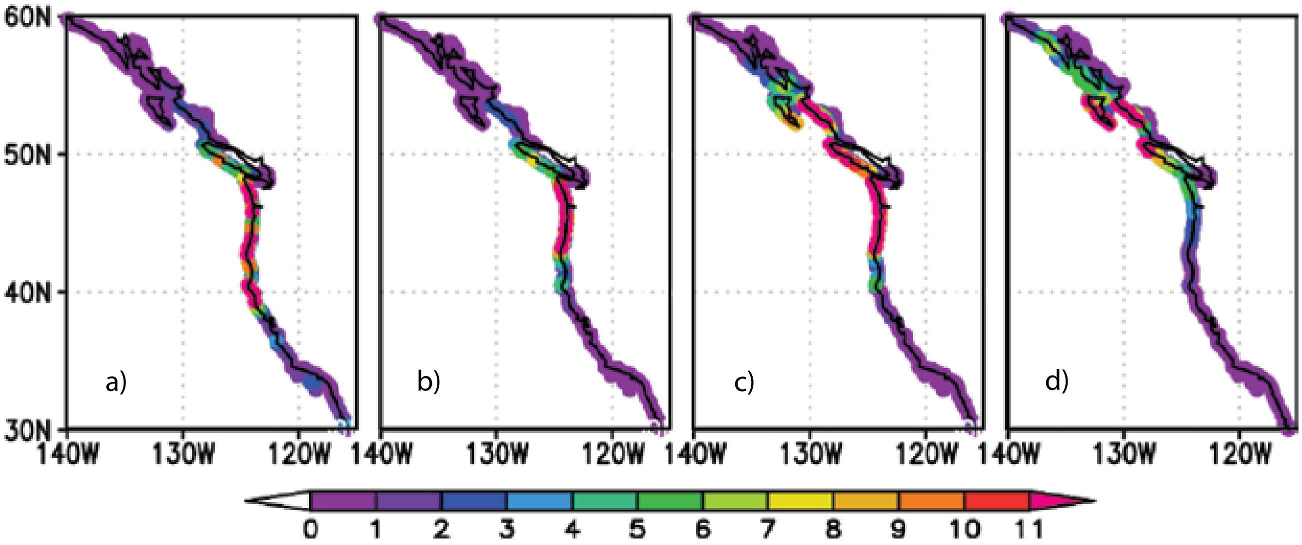


Figure 2-18. Relative amount of model tracer that washed onto the Pacific North American coast in the SCUD runs between March 11, 2011 and March 10, 2016. Windage values are (a) 0%, (b) 1.6%, (c) 3%, and (d) 4.5%. Units are conventional.

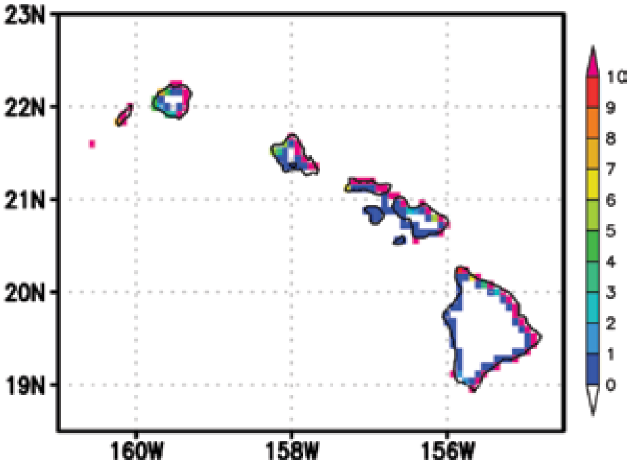


Figure 2-19. Relative amount of model tracer (with 3.0% windage) that washed onto the Hawaiian coastline in the SCUD runs between March 11, 2011 and March 10, 2016. Units are conventional.

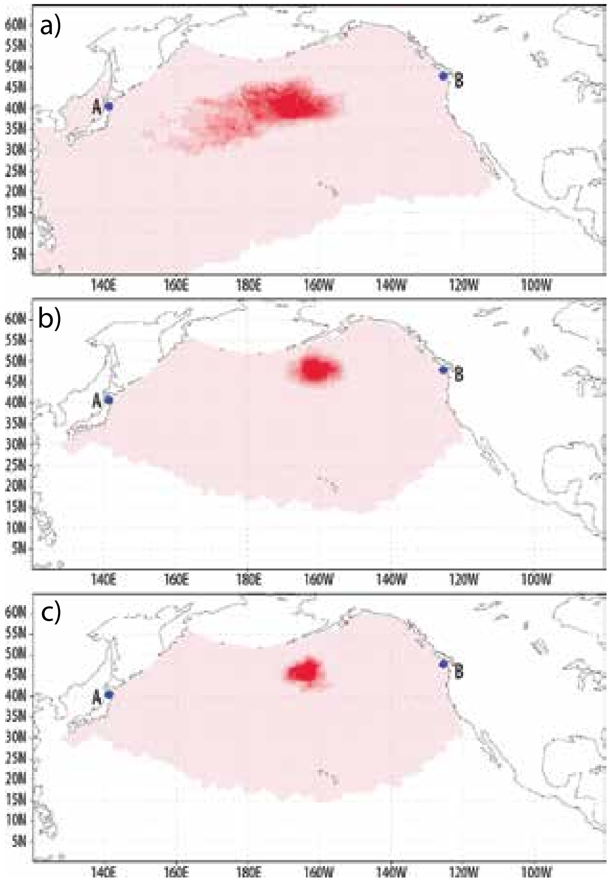
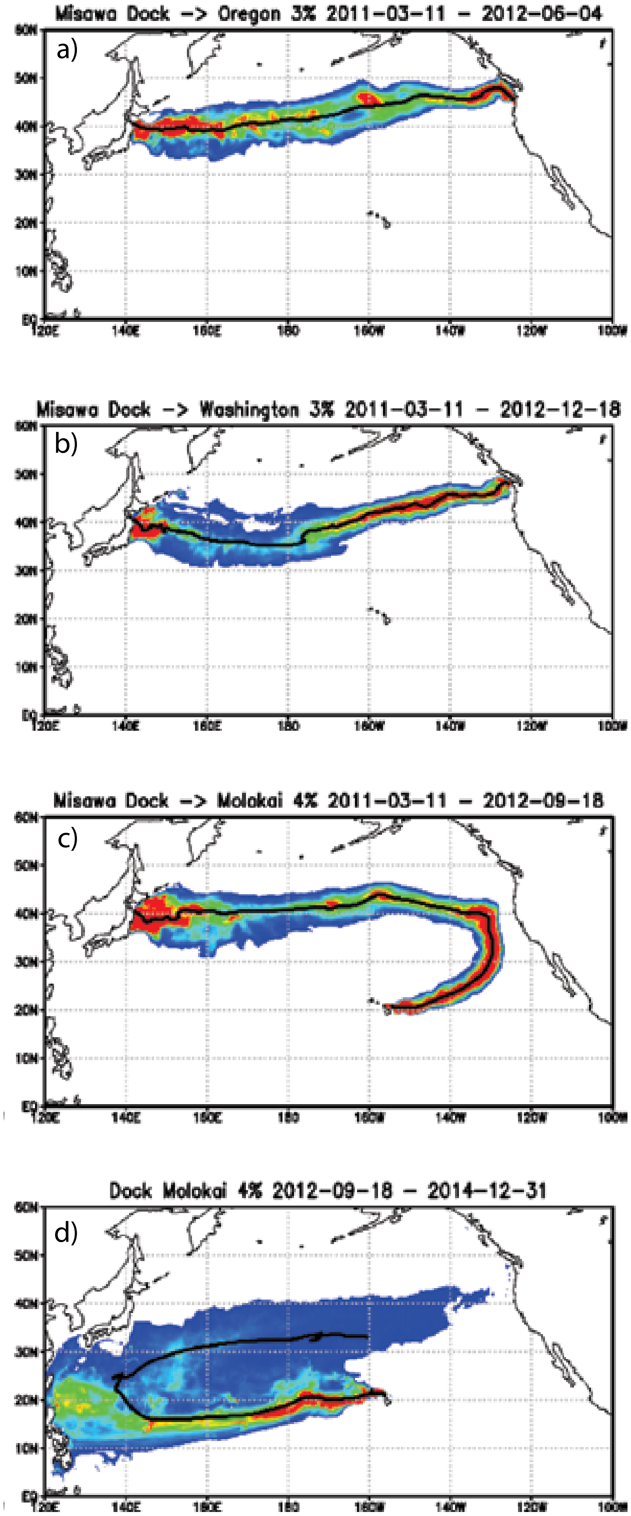


Figure 2-20. Probability density functions (PDFs) of model particle locations on January 1, 2012 for the particles that (a) started from Japan on March 11, 2011 (point A), (b) ended in Washington state on August 15, 2012 (point B), and (c) combined probabilities of particles that started at point A and ended at point B.


Misawa Dock -> Oregon 3% 2011-03-11 - 2012-06-04

Misawa Dock -> Washington 3% 2011-03-11 - 2012-12-18

Misawa Dock -> Molokai 4% 2011-03-11 - 2012-09-18

Dock Molokai 4% 2012-09-18 - 2014-12-31

Figure 2-21. Probable visited locations (colours) and trajectories (lines) for Misawa docks, reported from (a) Oregon, (b) Washington, and (c) Hawaii. (d) Probable trajectory of the Molokai dock after drifting between Hawaiian Islands.

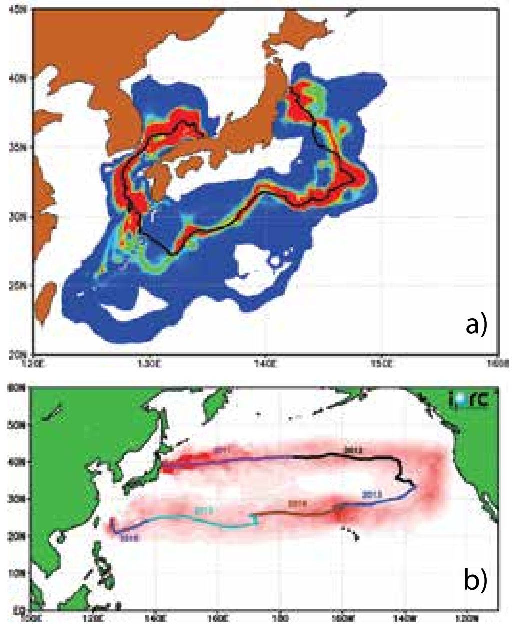


Figure 2-22. Probable visited locations (colours) and trajectories (lines) for the two JTMD boats found on (a) December 31, 2011 near Kami on the west coast of Japan and (b) May 12, 2016 in Okinawa.

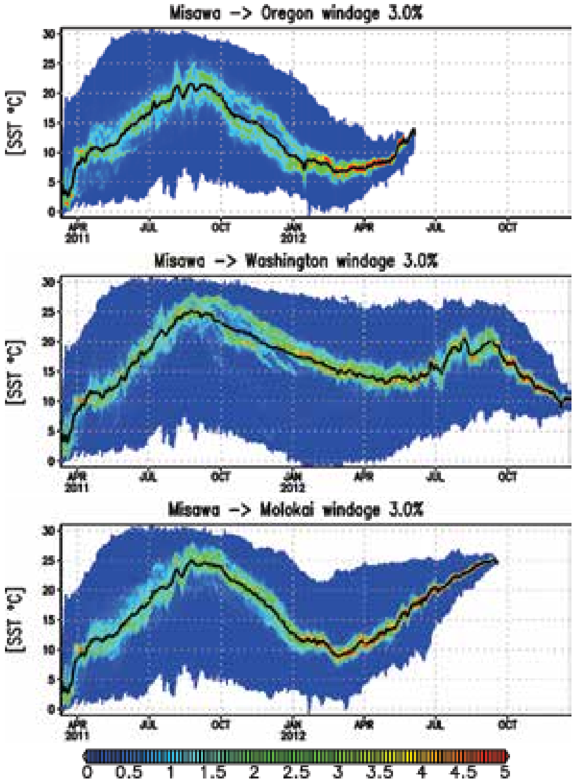


Figure 2-23. Probability density functions (colours) and probable timeline (lines) of satellite sea surface temperature (SST) experienced by Misawa docks along their probable paths.

Using model tracer for probabilistic study of motion of JTMD items

Objects floating on the ocean surface are moved by many processes, some of which are stochastic by their nature. Errors and unknown factors also add to the stochasticity of the debris path. To take these factors into account, model experiments operating with particles introduce a "random walk" and launch an ensemble rather than a single particle. In this project we developed a new technique that proved to be useful in such practical tasks as the determination of a probable path of any observed JTMD item. The method was based on experiments with the model tracer launched at a single point or from a distributed source, in which tracer concentration was interpreted as a probability density function (PDF) for a single particle to be found at a given location at a given time.

The example of a particle that started from northern Honshu on March 11, 2011 (point A) is illustrated by Figure 2-20a. The map of the model tracer concentration calculated for January 1, 2012 outlined probable locations of a particle at that moment. Any additional information about particular JTMD items can be incorporated into this probabilistic technique to produce more sophisticated assessments. For example, for a JTMD item found August 15, 2012 on the shores of Washington State (point B, Figure 2-20b) calculations using reverse equations demonstrate its probable location on January 1, 2012. The two PDFs can be combined, and their product (logical operation "AND") in Figure 2-20c illustrates probable intermediate locations of a particle traveling from point A to point B. Figure 2-21 shows probable trajectories and visited locations calculated using the techniques applied to the three Misawa docks that all started from the same harbor in northern Honshu and were later reported from Oregon, Washington and Hawaii.

Our new techniques allow the addition of practically any weak or strong constraints for various applications. If the exact start point is not known, a probable distribution for the source location can be calculated or, the fate of JTMD can be assessed even if it is not confirmed by observations. For example, our method suggested that the Misawa dock reported in 2012 north of Molokai, Hawaii, ended (with 90% probability) in the northeastern Pacific (Figure 2-21d). In the course of the ADRIFT project, this technique demonstrated its power in many difficult applications and was able to provide an estimate in the cases when answers were not obvious. For example, it successfully identified the likely route of a JTMD boat found near Kami, Japan at the end of 2011 (Figure 2-22a) and a similar boat (Figure 2-22b) that was found in Okinawa in 2016 (i.e., five years later).

Similarly, other information can be derived from our methods. For example, Figure 2-23 shows the PDF and probable timelines of the sea surface temperature (SST), estimated using AMSR (Advanced Microwave Scanning Radiometer) satellite data, along the probable trajectory of the three Misawa docks. These timelines can be used to evaluate the chances of survival of species colonizing particular debris items and can be validated against actual samples. Probable paths and oceanographic conditions along the paths were calculated for all reports collected

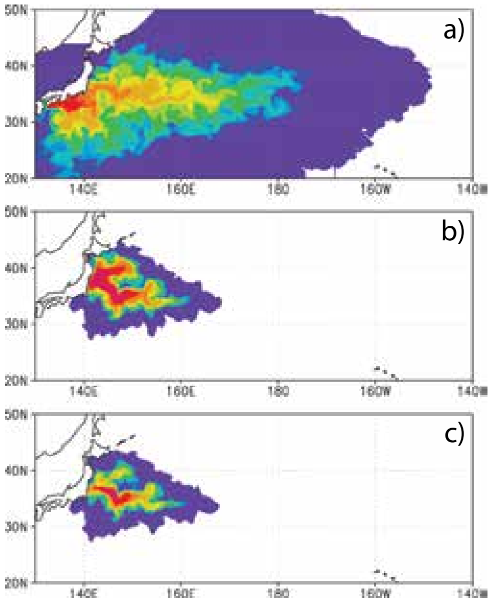


Figure 2-24. Interaction between tsunami debris and subtropical coastal species in SCUD simulations. (a) March 11, 2011 concentration of model larvae, continuously released from the southern coast of Japan and having a 7-day e-folding life span, (b) concentration of JTMD tracer with 2% windage, and (c) strength of debris–larvae interaction, with red representing highest interaction strength.

in the ADRIFT "biofouling" dataset and used in the vector risk assessment research (see Chapter 16). By their nature, accuracy of probabilistic methods was small for a single object but increased with the size of an ensemble or if additional information was available. In future studies, information about species found on JTMD items can be added to improve estimates of probable paths.

Biological interactions with JTMD

The biological samples collected from JTMD items inspired many difficult questions. For example, the Misawa dock found in Oregon hosted not only cold-water species characteristic of northern Honshu but also subtropical species, suggesting that during its drift the dock spent some time in warm water (see Chapter 7). To study the interaction between JTMD and subtropical species, we simulated advection of larvae from the southern coast of Japan by setting up a continuous tracer source (at 0% windage) along the southern Honshu, Shikoku, and Kyushu islands. Despite the short life span of the larvae (7-day e-folding decay), they were advected hundreds of kilometers eastward by the fast Kuroshio Extension (Figure 2-24a). JTMD tracer released north of the Kuroshio Extension also drifted mainly eastward but the effect of the higher windage also pushed it southward (Figure 2-24b). As a result, there was a strong interaction between tsunami debris and subtropical coastal species along the Kuroshio Extension axis between 140° and 160°E (Figure 2-24c). Once attached to a JTMD item, larvae could develop into adult species and continue the journey toward North America and Hawaii.

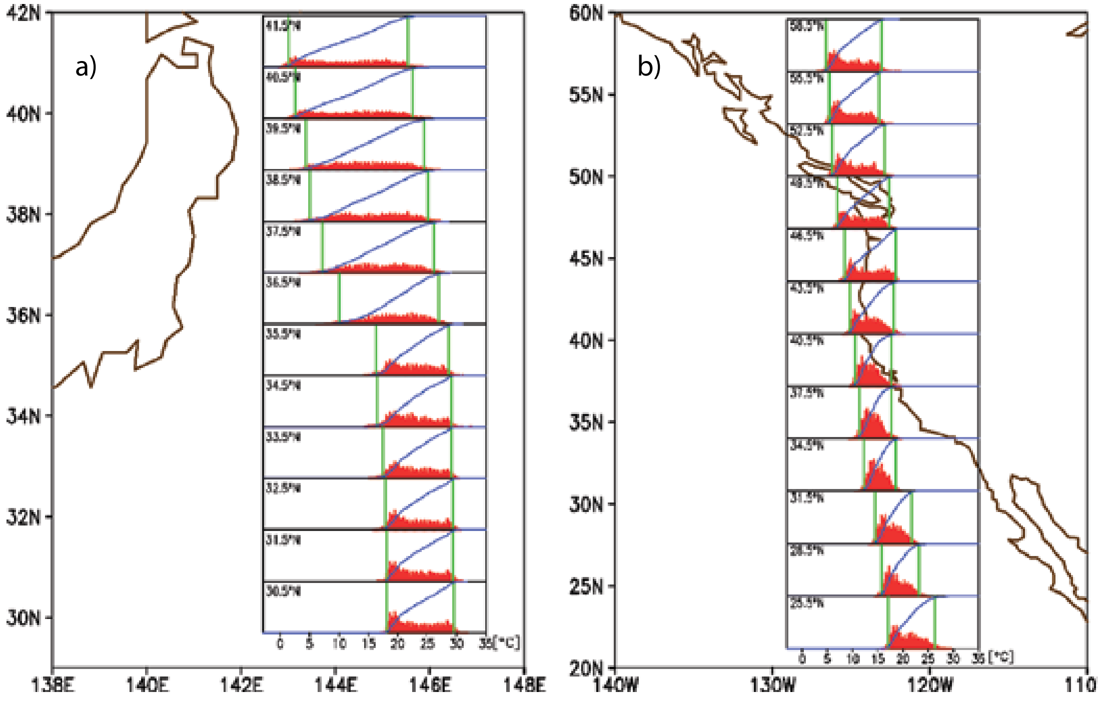


Figure 2-25. Probability density function (PDF) (red bars) of sea surface temperature (SST) at different locations along (a) the east coast of Japan and (b) the Pacific coast of North America, calculated from the AMSR satellite data. Blue lines are cumulative PDFs and green bars indicate SST limits after removing outliers.

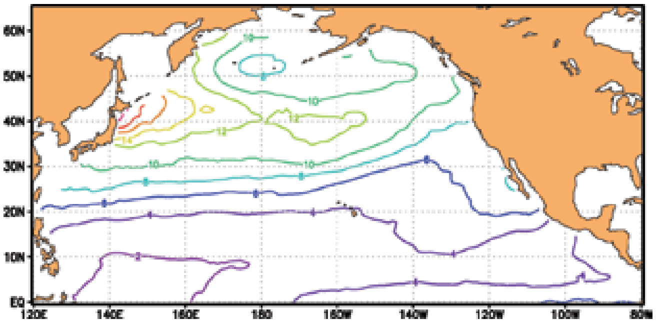


Figure 2-26. Sea surface temperature (SST) range (°C) from AMSR satellite data.

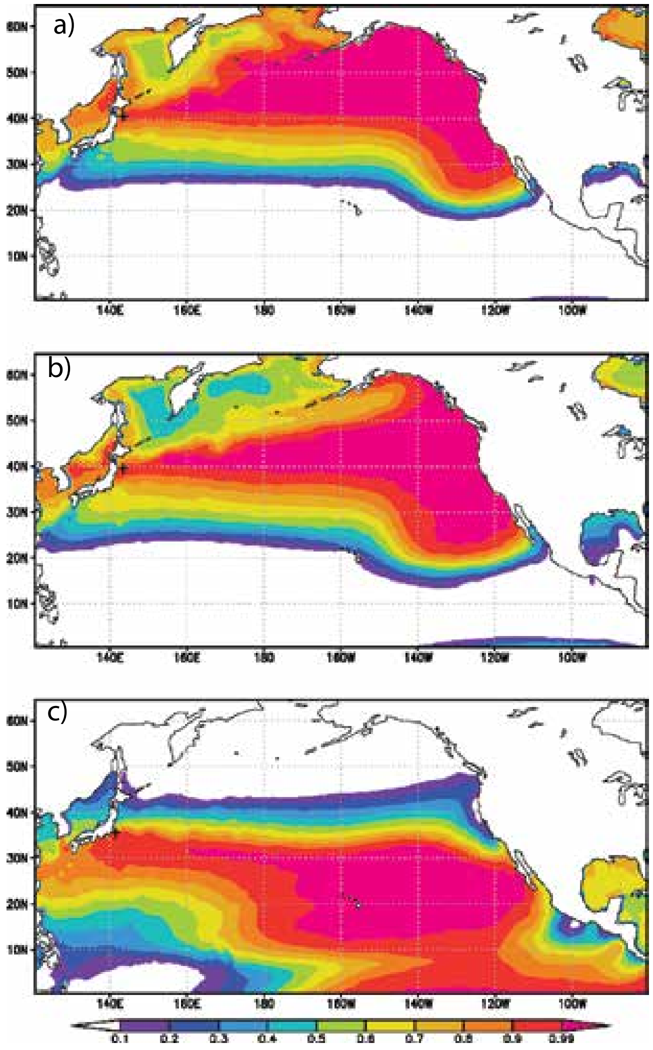


Figure 2-27. Degree of the sea surface temperature (SST) match with the climatology at select locations east of Japan (marked with a cross), calculated using AMSR satellite data. Model origin locations: (a) 143.5°E, 40.5°N, (b) 143.5°E, 39.5°N, and (c) 141.5°E, 35.5°N.

Temperature match between Japan, North America and Hawaii

The climate match between source ecoregions in Japan and destination ecoregions in North American and Hawaii may affect the ability of species transported with JTMD to survive and establish. Temperature is a critical parameter that has an almost immediate effect on the survival of species. We calculated climatologies of temperature in the North Pacific and their correspondence to the temperature statistics in the areas in Japan affected by the Great Japan Tsunami of 2011. Sea surface temperature, observed by the AMSR satellite mission, varies with latitude and differs on the western and eastern sides of the North Pacific (Figure 2-25). Importantly, the area in Japan located between 38° and 40°N and corresponding to maximum JTMD generation (Figure 2-1) also had the broadest SST range, spanning 20°C, with a very strong seasonal cycle with temperatures below 5°C in winter and above 25°C in summer. The SST range east of Japan exceeded the one in North America as much as two times (Figure 2-26). Generally speaking, this means that coastal species that are able to survive in the northeastern Honshu ecoregion may be resilient to temperature conditions practically anywhere in the Northeast Pacific north of 30°N. This suggestion was further confirmed by Figure 2-27, which shows that nearshore SST conditions between Baja California and Alaska all fit in the temperature range of the east coast of Japan between 39° and 41°N. This pattern does not include Hawaii, where tropical temperatures are significantly higher, implying that species from the north of Japan will be less likely to survive. However, subtropical species that may have been picked up by the northern JTMD in the Kuroshio Extension (Figure 2-24) could find a better climate match with the water temperature in Hawaii (Figure 2-27c). Open-ocean patterns of high-match areas were consistent with the JTMD paths in the first years after the tsunami (Figures 2-5 to 2-7). However, on a longer run, JTMD remaining in the garbage patch or in the larger Subtropical Gyre were exposed to conditions that may or may not fit into the SST ranges in the ecoregions east and south of Honshu. Long-term survival of coastal species in the open ocean is an interesting and difficult task that requires future investigation and, importantly, sample collection from marine debris in the open ocean.

Conclusions

During the three years of the ADRIFT project, our modeling study progressed from qualitative illustrations of the propagation and fate of JTMD to specialized model schemes and settings as well as model data analysis techniques, which provided quantitative answers on specific practical questions. New techniques now allow model verification and scaling using observational data and are available for the investigation of drift patterns and timelines of landings of large categories of JTMD as well as oceanographic conditions along probable paths of individual items. By combining ocean circulation with parameters such as sea surface temperature, salinity, and chlorophyll, we facilitated assessment of the risk of JTMD for species introductions.

A complete set of model solution maps and data is available at http://iprc.soest.hawaii.edu/MarineDebrisModels.


NOAA

Acknowledgements

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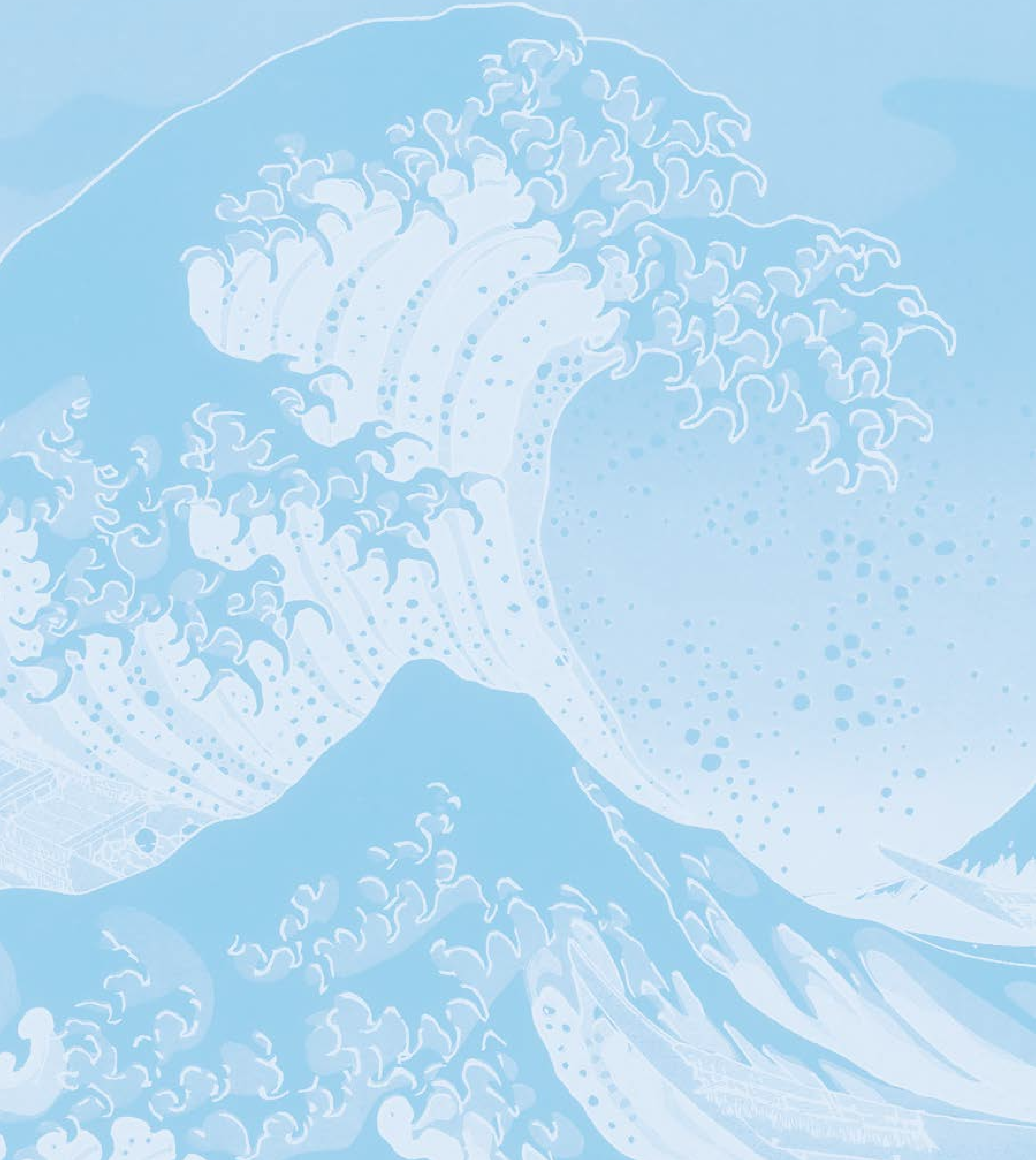

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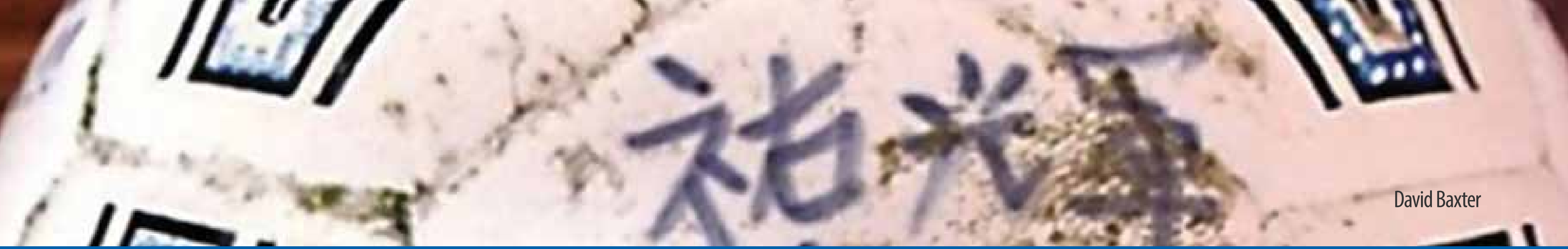
David Baxter

THEME II – Arrival of Debris

Chapter 3: Shoreline monitoring of debris arrival in North America and Hawaii[1]

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Abstract

Marine debris is one of the leading threats to the ocean, and the Great Japan Tsunami of 2011 washed away an estimated 5 million tons of debris in a single, tragic event. Here we used shoreline surveys, disaster debris reports and oceanographic modeling to investigate the temporal and spacial trends in the arrival of tsunami marine debris. The increase in debris influx to surveyed Pacific North American and Hawaiian shorelines was substantial and significant, representing a 10-fold increase over the baseline in northern Washington State where a long-term dataset was available. The tsunami event brought different types of debris along the coast, with high-windage items dominant in Alaska and British Columbia and large, medium-windage items in Washington State and Oregon. The temporal peaks in measured shoreline debris and debris reports match the ocean drift model solutions. Mitigation and monitoring activities, such as shoreline surveys, provide crucial data, and monitoring for potential impacts should be continued in the future.

Introduction

The Great East Japan Earthquake and resulting tsunami washed an estimated 5 million tons of debris into the Pacific Ocean (MoE, 2012). This single event delivered an amount in the range of the estimated global debris input to the ocean each year (4.8 to 12.7 million metric tons) and more than any single country, other than China, was estimated to produce in a single year (Jambeck et al., 2015). Marine debris associated with this unique natural history event differs from general marine debris because the source and date of dislodgment or entry into the ocean are both known and fixed. Additionally, the predominant drift in the North Pacific is eastward toward the Pacific coast of North America and the Hawaiian Islands (Howell et al., 2012), and this drift can be modeled to estimate the spatial and temporal trends in shoreline interception (Bagulayan et al., 2012).

The first confirmed tsunami debris item to be found on shore, a soccer ball, landed in Alaska in March 2012 (NOAA Disaster Debris Reports, unpublished data). Since then, anecdotal reports and documented sightings suggest that the influx of marine debris in the years after the tsunami was substantial and unprecedented but there have been no attempts to measure and analyze the amount of incoming debris. Large debris items (e.g., vessels, floating docks) present a hazard to navigation and may act as floating islands that carry fouling and hitchhiking organisms that pose a risk to native ecosystems. Smaller debris items (e.g., lumber and building material) are more difficult to trace, but the type of debris from the tsunami is generally different than baseline marine debris.

Monitoring and removal of shoreline debris has been ongoing since the 1990s (Morishige et al., 2007; Ribic et al., 2012). After the tsunami occurred, sightings of debris were recorded and, if possible, traced to the original owner and confirmed as lost during the tsunami. In the wake of the Great Japan Tsunami of 2011, this ongoing research provides an opportunity to analyze the landing and trends in amount of marine debris. Quantifying and categorizing the influx of tsunami-associated debris will assist in the prioritization of research on marine debris impacts, document impacts to wildlife and ecosystems, prioritize cleanups and removal activities and investigate the potential for the introduction of invasive species.

Here we analyze available data on the timing, spatial distribution and debris types arriving on Pacific North American and Hawaiian shorelines in order to:

1. Quantify the amount, distribution and timing of debris landfall,
2. Estimate debris landfall attributable to the Great Japan Tsunami of 2011, and
3. Compare to oceanographic modeling predictions.

In short, we ask whether we can detect the signal of the tsunami debris against the background of ongoing marine debris and generalize sparse observational reports into a bigger picture of the event.

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[1] A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 26-32.

Materials and Methods

Shoreline monitoring

The ongoing NOAA marine debris shoreline survey is a rapid, quantitative beach survey which uses trained community volunteer organizations to collect standardized and consistent data. NOAA's current shoreline Marine Debris Monitoring and Assessment Project (MDMAP) began in 2011 and continues through the present (Lippiatt et al., 2013). The MDMAP accumulation survey protocol measures the net accumulation of all types of marine debris items on a site's 100 m stretch of beach every 28 days. All debris items are recorded and removed from the shoreline. Surveys are conducted by citizen science groups or government staff, and depending on weather and tides, the amount of beach and monthly schedule sometimes varies (Opfer et al., 2012). For each survey, the incidence of large items (greater than 30 cm) is specifically recorded, and additional information and photos of the items are provided by surveyors. Between March 2012 and December 2015, over 1,100 surveys were conducted at more than 120 sites in Alaska, British Columbia, Washington, Oregon, California and Hawaii. The NOAA dataset was analyzed for trends in the distribution and abundance of debris influx and type over time and along the Pacific coast of North America and the islands of Hawaii.

Long-term spatially distributed marine debris monitoring datasets are rare, so a dataset maintained by the Olympic Coast National Marine Sanctuary was used to establish a baseline of marine debris influx prior to the tsunami event. This survey protocol recorded marine debris indicator items at sites in northern Washington from 2001 to 2011. All debris was removed from a 500 m stretch of beach at each site, and the number of debris items in each of the 30 indicator categories was recorded (supplementary materials in Appendix 3-1). Indicator items were chosen to represent different sources of debris (land, ocean, and general source debris); the National Marine Debris Monitoring Program (NMDMP; pre-2011) protocol is described in more detail by Ribic et al. (2012).

In order to compare baseline debris influx with that after the tsunami event, we compared the two sets of debris categories and removed or combined categories and the data contained within as needed (see supplementary materials in Appendix 3-1). The level of effort is consistent across both formal monitoring programs (MDMAP and NMDMP) as all items of interest from the survey area were recorded regardless of the number of surveyors. The NOAA MDMAP protocol records information on a more diverse set of debris items; only those fields that overlap with the NMDMP protocol were compared (Appendix 3.1, Supplementary Table 3-1). We identified common sites between the two survey timelines, and then analyzed the spatial and temporal trends in marine debris influx. In total, 47 beaches were surveyed and 11 NMDMP sites continued to be surveyed with the new protocol (see supplementary materials in Appendix 3-1). The mean number of debris items recorded per 100 m stretch of beach per day was analyzed, and ANOVA with Tukey's post-hoc statistical tests were used to test for differences between years and states or provinces.

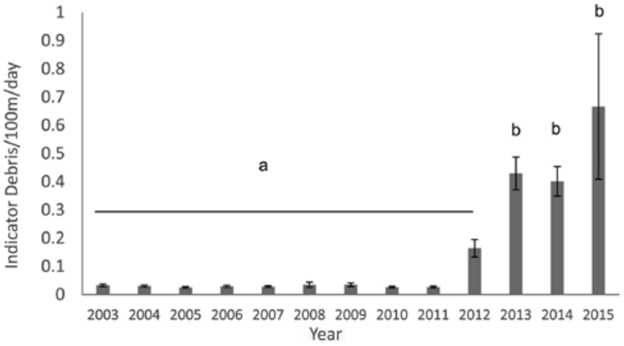

Figure 3-1. Mean yearly debris influx of indicator items from 2003 to 2015 at sites in northern Washington State. Letters denote different groups using Tukey's HSD (honestly significant difference) post-hoc statistical comparisons.

After the Great Japan Tsunami of 2011 occurred, NOAA established a reporting system for public sightings of suspected tsunami debris items. Reports were received by email and maintained in a database, hereafter referred to as "disaster debris reports". Records as of April 13, 2016 were analyzed for temporal and spatial trends and compared to the shoreline monitoring results. Confirmed tsunami debris items were those with identifying marks that could be traced to items known to be lost during the tsunami event, through diplomatic channels.

Modeling tsunami debris

Simulations of the Surface Currents from a Diagnostic (SCUD; Maximenko and Hafner, 2010) model were used to study particle and tracer motions after release on March 11, 2011 along the east coast of Honshu, Japan. SCUD is an empirical, diagnostic model (developed at the International Pacific Research Center, University of Hawaii) that is forced with data from satellite altimetry (sea level anomaly) and scatterometry (vector wind) and calibrated on a ¼-degree global grid using trajectories of satellite-tracked drifting buoys (Maximenko and Hafner, 2010). The model experiments used 61 values of windage ranging between 0 and 6%. We compared the monthly model predictions to observations of debris influx during the shoreline surveys and the sightings reported using Spearman's rank correlations.

Results

Debris monitoring

The debris landings after 2013 were significantly different than 2012 and prior (One-way ANOVA, $F = 3.992$, df = 12, $p < 0.001$) (Figure 3-1). There was a sharp increase in the influx of indicator debris items, from mean 0.03 items per 100 m of shoreline per day between 2003 and 2012 to mean 0.29 debris items per 100 m per day from 2013 to 2015. This was an almost 10-fold increase in debris influx to sites in northern Washington State over that recorded in the 9-year period prior to the tsunami event. Prior to the peak in indicator debris items (May 2012), monthly mean debris influx ranged from 0.01 to 0.08 indicator debris items per 100 m per day and after the peak indicator debris influx ranged from 0 to 0.78 debris items per 100 m per day (Figure 3-2).

Along the Pacific coast of the U.S., there were peaks in all debris items (not just indicator items) in May 2012 and early in 2013, and smaller peaks in May 2014 and late 2014 (Figure 3-2). Across all North American study sites, the recorded mean debris influx peaked in July 2012 at 13.8 debris items per 100 m per day. Mean monthly debris influx for all debris items (2012–2015) was 2.7 debris items per 100 m per day (ranging from 0.5 to 13.8 debris items per 100 m per day).

Across all the states and province of study, Hawaii received the highest mean debris items over the post-tsunami study period (2012–2015; Figure 3-3). British Columbia had the second highest mean debris influx in this time period, driven by a few surveys in the islands of Haida Gwaii (northern British Columbia), with high numbers of large Styrofoam pieces. Alaska had few accumulation surveys to analyze and was not included in the figures. The total amount of debris arriving monthly to actively monitored North American coastlines in the post-tsunami months ranged from 150 to 1,951 items (Figure 3-4). The cumulative arrival of documented debris items to surveyed North American coastlines was more than 93,000 items (Figure 3.4).

Shoreline survey data: Large items

The incidence of large debris items (larger than 30 cm) in MDMAP surveys was highest in Washington State (28 items per shoreline, 736 items total), followed by California (7.7 items per shoreline, 185 items total). Across regions, the highest arrival of large items occurred in 2013 and 2014 (Figure 3-5). The prevalence of large items in California was not likely related to tsunami debris as the survey notes from California made no mention of possible tsunami debris items, and many of the largest items were unable to be removed and were repeatedly noted in surveys. Large items sightings from monitoring surveys were concentrated at sites in Washington, and very few large items were reported in Hawaii surveys (Figure 3-5). This was a different pattern than that for debris smaller than 30 cm, where large numbers of debris items were found on surveys in Hawaii. The number of large items has significant spatial autocorrelation (Moran's $I = 0.0328$, Z-score = 5.704, $p < 0.00001$), meaning that neighbouring sites have similar numbers of large items within a distance threshold of 24.5 km.

Disaster debris reports

Reports of disaster debris peaked in June 2012, March 2013, and May 2014 with at least one confirmed debris item from the Great Japan Tsunami of 2011 in each of the temporal peaks (Figure 3-6). The sightings were significantly spatially clustered at a mean distance of 16.268 km (nearest neighbour Euclidean distance: observed mean distance = 16.3 km, expected mean distance = 137.205 km, nearest neighbour ratio = 0.119, Z-score = –64.849, $p < 0.00001$). Miscellaneous or mixed debris was the most commonly reported disaster debris, followed by consumer debris (Table 3-1). Vessels were the most common type of debris that could be confirmed as lost during the Great Japan Tsunami of 2011 (33 confirmed out of 202 reported). Many of these vessels had registration numbers or vessel names that could be more easily traced and officially confirmed as tsunami debris.

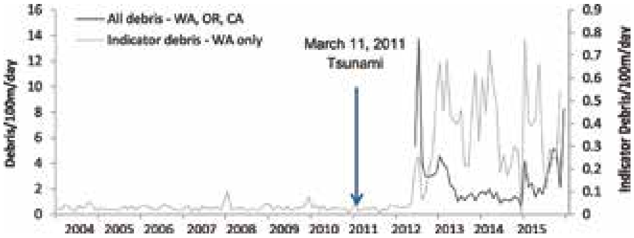

Figure 3-2. Mean monthly debris influx of indicator items (indicator debris items per 100 m per day) from 2004 to 2015 at sites in northern Washington State (grey line) and mean monthly influx of all debris items (debris items per 100 m per day) for Washington (WA), Oregon (OR) and California (CA) from 2012 to 2015 (black line).

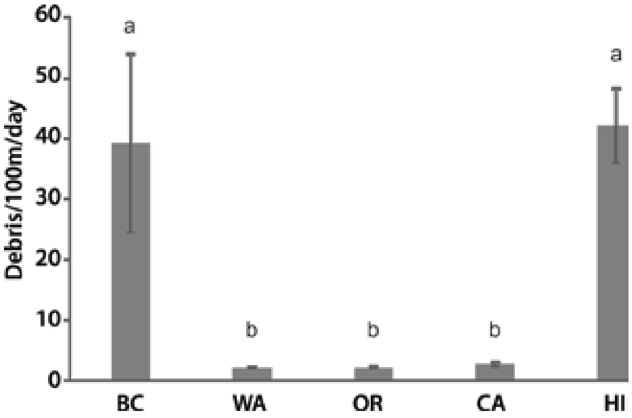

Figure 3-3. Mean debris item arrival (debris per 100 m per day) from 2012 to 2015 by province/state. BC = British Columbia, WA = Washington State, OR = Oregon, CA = California, and HI = Hawaii. Letters denote statistically different subgroups.

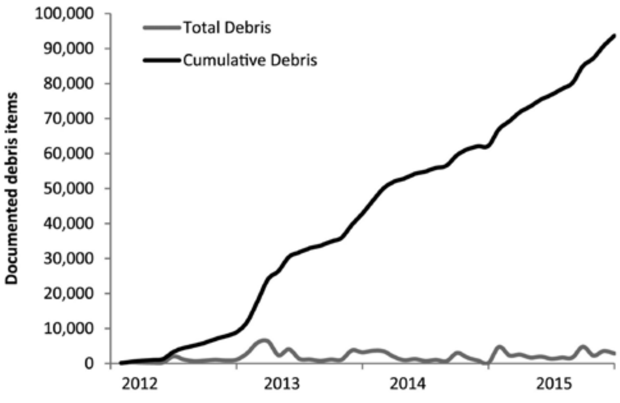

Figure 3-4. Total (grey) and cumulative (black) number of documented debris items arriving to monitored shoreline sites (excluding Hawaii) over time (2012–2015).

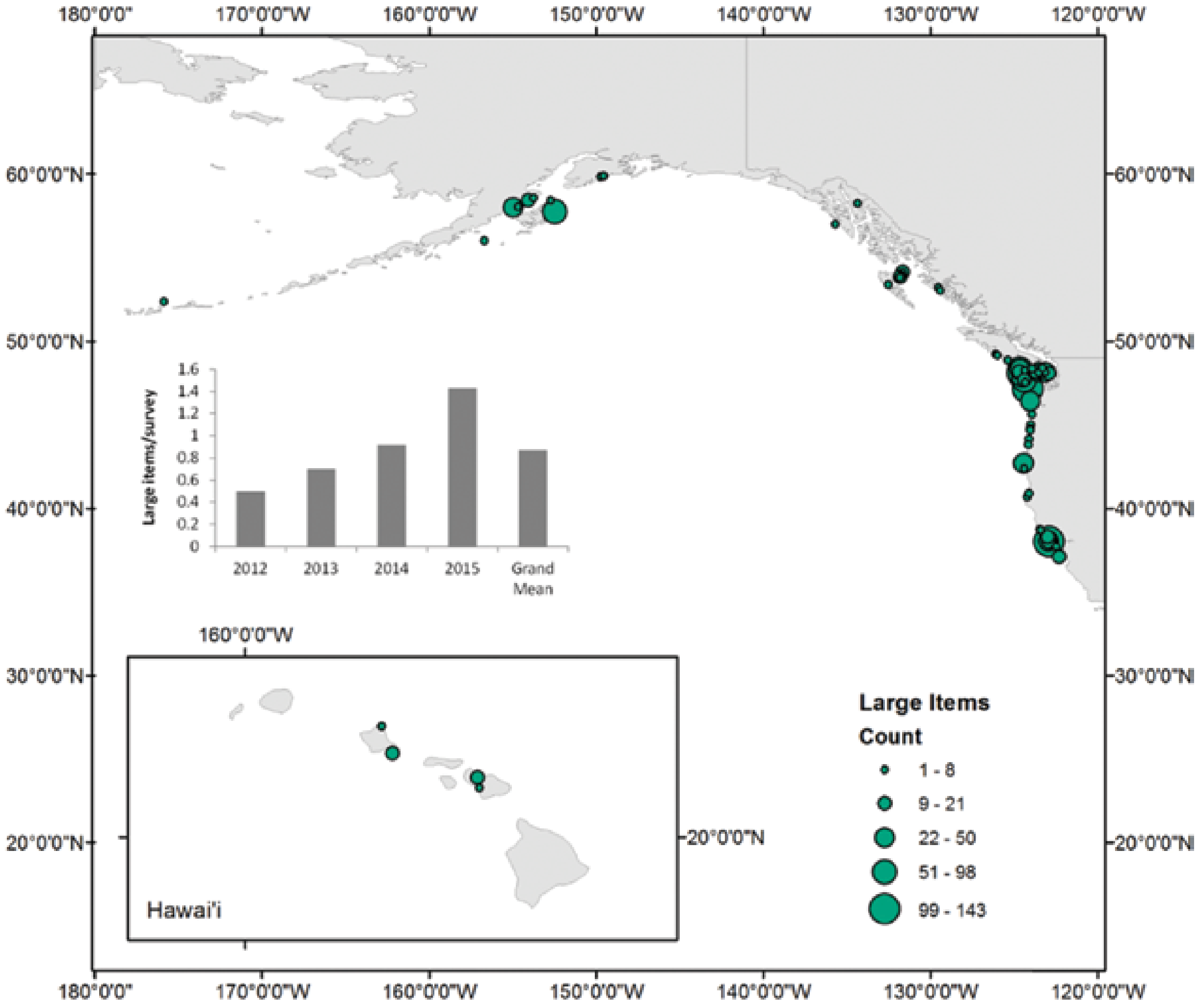

Figure 3-5. Map of large item reports per survey along the Pacific coast of North America; circles of increasing size represent increasing numbers of large items recorded. Inset shows large items per survey between 2012 and 2015 in Hawaii.

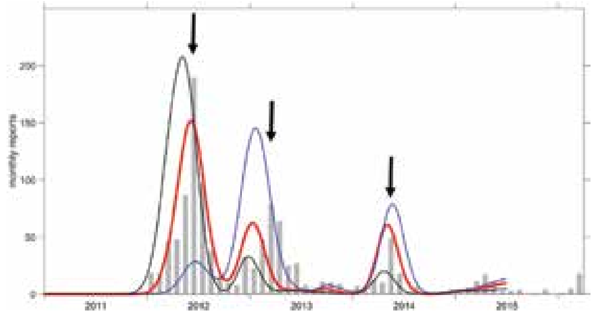

Figure 3-6. Temporal peaks in disaster debris reports for North American landfall (grey bars), as of April 13, 2016, and simulated monthly debris arrival from the SCUD model. Lines represent model solutions for differing windage values: 1.5% (blue), 2.2% (red), and 3.0% (black). Arrows indicate temporal peaks in disaster debris reports.

Table 3-1. Disaster debris reports by type to the NOAA Marine Debris hotline and their status as confirmed or not confirmed lost during the Great Japan Tsunami of 2011, as of April 13, 2016.

Debris type	**Not confirmed**	**Confirmed**	**Total**
Construction debris	76	2	78
Consumer debris	421	6	427
Fishing gear	257	4	257
Misc. or mixed debris	644	15	659
Vessel	169	33	202
Total	**1567**	**60**	**1627**


Nikolai Maximenko

Modeling debris arrivals

The SCUD model solutions corresponded with observations by capturing all three main temporal peaks in the disaster debris reports and the shoreline debris arrival data, although they disagree somewhat in the magnitude of the peaks (Figure 3-6). Model solution indicates temporal peaks in June 2012, January 2013, and May 2014 (arrows in Figure 3-6). Interestingly, for 2013 the model solutions lead the observations by 2 to 3 months. The optimal windage for the disaster debris reports is 2.2% (red line in Figure 3-6). The three peaks in MDMAP shoreline debris data after the tsunami (June 2012, March 2013, and March 2014) are similar to the peaks in disaster debris reported to NOAA (June 2012, March 2013, and May 2014) and these peaks are consistent with modeling predictions. There was a significant positive correlation between monthly model predictions (2.2% windage) and monthly total disaster debris reports (Spearman's $\rho = 0.699$, $p < 0.001$, $R^2 = 0.668$) and observed shoreline debris influx (Spearman's $\rho = 0.517$, $\rho = 0.001$, $R^2 = 0.441$).

High-windage tracer (black line in Figure 3-6) arrives earlier than low windage (blue line) and high windage more readily lands on shore while low windage tends to remain in the ocean for longer durations. As a consequence, the magnitude of high-windage peaks decays faster with time while low-windage arrivals can continue over many years. The changing composition of JTMD landing over time may cause changes in the optimal windage, leading to mismatch between model solutions and observations.

Discussion

Unprecedented influx of marine debris

The Great Japan Tsunami of 2011 caused a significant and substantial influx of debris to North American shorelines along the Pacific coast, and the evidence presented here is in agreement with anecdotal reports of high abundances and unusual debris types outside the normal range of cultural memory. In the locations where long-term data exist, a more than 10-fold increase (from 0.02 to 0.29 indicator items) over the baseline level was recorded. This increase is likely a conservative estimate as it is based on only a subset of debris indicator items. Debris types unique to the tsunami event, such as lumber, were not recorded in the original NMDMP protocol. The concordance between the different data sources and modeling predictions suggests that the influx is a result of the tsunami event and is outside the baseline influx of marine debris experienced on the Pacific coast of North America and in Hawaii.

Prior to the peak in indicator debris items attributed to the tsunami (May 2012), debris influx was in the range previously reported for the Pacific North American coast. Ribic et al. (2012) reported a mean of 0.2 marine debris indicator items per 100 m per day for the Pacific North American coast from 1998 to 2007. After the tsunami, indicator items averaged 0.29 items per 100 m per day, and reached as high as 4.1 debris items per 100 m per day. After tsunami debris began to arrive, indicator debris at sites in northern Washington increased 10-fold. The cumulative arrival of debris to the Pacific North American coast was recorded only at those sites undergoing shoreline monitoring and removal. Even at this small subset of available shoreline, almost 100,000 debris items were recorded. Those shorelines remotely located or inaccessible to cleanup groups may be the most affected by remaining debris loads and may experience greater impacts from debris accumulation (Gall and Thompson, 2015). Additionally, debris remaining at these sites have the potential to become re-suspended and make landfall elsewhere in the North Pacific (Kako et al., 2010), acting as secondary sources of debris.

Therefore, although a significant background level of marine debris existed prior to the tsunami, this one event increased the debris load across the entire region. North Pacific ecosystems are believed to be under pressure from the substantial influx of marine debris, microplastics and fishing gear causing entanglement of marine mammals and birds, toxicity issues and the possibility of introduction of rafting species (Gregory, 2009; Gall and Thompson, 2015). This substantial increase in debris agrees with the anecdotal evidence that there was a large increase and different diversity of debris landing after the

tsunami event – increased building materials, vessels, and large pieces of Styrofoam in particular.

There was large spatial and temporal variation in debris influx after the first peak of tsunami debris was recorded. In keeping with general marine debris trends in this region (Ribic et al., 2012), across the MDMAP monitoring sites, overall debris influx post-tsunami was highest in Hawaii. This is likely a result of its proximity to the Central Pacific Gyre with temporal variation attributed to the El Niño–Southern Oscillation (ENSO) cycle (Ribic et al., 2012). The influx of large items and disaster debris reports was higher than expected for Washington State. Disaster debris reports vary with public interest in the issue and shoreline visitation, but are an indication of increased debris. Large items with medium windage parameters were expected to make landfall in Washington and Oregon. Model predictions suggest that windage of landed debris increases with latitude so that high-windage items are more common in Alaska (e.g., large Styrofoam pieces) and low-windage items more common in Washington, Oregon and California (low profile docks and upside-down vessels). The oceanography models predicted that items of similar windage values, such as small skiffs, would be expected to concentrate in Washington and Oregon, and more than 150 of these have been documented landing in these areas (see Chapter 2). Note that there were few surveys in Alaska and northern British Columbia due to the remote nature of these coastlines and therefore, it is difficult to document trends for these regions.

Variation in storm season duration and strength and the timing of the spring transition were responsible for the observed temporal trends in debris arrival to North America (see Chapter 4; Kako et al., 2018). Temporal trends in Hawaii were more variable, and the peaks from the Great Japan Tsunami of 2011 were undetectable against the background variation of marine debris influx. Hawaii receives more ocean-based debris than other regions within the North Pacific (Ribic et al., 2012; Blickley et al., 2016) because of its proximity to the Central Pacific Gyre and the so-called "garbage patch". Therefore, the signal from the tsunami may be harder to detect against this high baseline influx.

There was a detectable signal of large debris items (larger than 30 cm) in the beach surveys and in the disaster debris reports, a portion of which were confirmed lost during the Great Japan Tsunami of 2011. These peaks match the modeling predictions, suggesting that they were real temporal waves of debris from the tsunami. An increase in large debris items was one of the major impacts from the tsunami, which distinguishes this event from background marine debris trends. Washington State was the most affected by large items, followed by California, while Oregon and Hawaii were the least affected by large items, as recorded in the beach surveys. There was some anecdotal evidence that suspected tsunami debris items may not have been as well reported to the disaster debris reporting system in Hawaii as in other states, and therefore, impacts from large items may be underestimated in Hawaii (N. Maximenko, pers. obs.).

While previous surveys documented declining or stable debris influx across the Pacific coast of North America and in Hawaii (Ribic et al., 2012), the Great Japan Tsunami of 2011 increased the debris loads to unprecedented levels for three years. Large debris items continued to make landfall in spring 2015, and many more remaining debris items have likely become entrained in the Central Pacific Gyre and will persist in the North Pacific for decades (see Chapter 2; Maximenko et al., 2018).

Uncertainty and assumptions

The shoreline monitoring site locations were opportunistic, chosen by partner organizations and volunteers interested in joining the MDMAP, and dependent on access, proximity and other desirable traits. Therefore, sampling sites are not evenly distributed across the area of interest and may not accurately represent the debris influx in more remote and sparsely populated areas. Some shorelines known to accumulate debris in British Columbia and Alaska are too remote to survey regularly or to participate in the accumulation surveys, which require complete removal of debris items. Additionally, some locations could not be accurately surveyed during the peak of tsunami debris arrival. Survey notes from Haida Gwaii in northern British Columbia recorded that the high amounts of large Styrofoam pieces were not fully enumerated as the focus became removal rather than an accurate accounting of the number of items.

The number of reported debris items confirmed as lost during the tsunami is certainly an underestimate. Not all debris items had identifying marks that could be used to trace their origin. The uncertainty surrounding additional items means that the true amount of tsunami debris washed up on Pacific North American and Hawaiian shorelines is unknown and difficult to quantify. The frequency of disaster debris reports varied with public and media interest. Although a significant amount of public outreach occurred, it is highly likely that items were found and never reported to NOAA or were never found at all. Sampling error was introduced because of untraceable debris items, i.e., debris that washed up and back out again before it could be sampled, and the household items similar to those regularly found in marine debris samples were also washed away in the tsunami. Additionally, there is an unknown quantity of debris items likely still floating in the open ocean and entrained in the Central Pacific Gyre. For example, of the four floating docks known to be lost from Misawa, northern Honshu during the tsunami, two washed ashore, one was sighted at sea but not recovered, and the fourth has never been seen and is presumed to have sunk.

The SCUD model demonstrated an impressive correspondence with observations by capturing all three main peaks, although they disagree somewhat with the magnitude of the peaks. They also systematically lead the observations by 2 to 3 months. These differences are not necessarily due to problems with the models. Lags in observations may reflect the influence of storms in bringing coastal debris onshore or delays in item identification and reporting resulting from the delay in developing public concern and awareness.

Conclusions

There was a significant increase in debris on the Pacific coast of North America and in Hawaii in the years following the Great Japan Tsunami of 2011, representing at least 10 times more debris than baseline levels. The spatial and temporal trends in disaster debris reports, shoreline debris surveys, and oceanographic modeling were in alignment. From this body of evidence, we conclude that the Great Japan Tsunami of 2011 produced a significant and substantial increase in debris influx to the shorelines of Pacific North America and Hawaii. Mitigation and monitoring activities, such as the shoreline surveys through MDMAP, provided crucial data in the wake of this unprecedented event, and monitoring for potential impacts, including those from potential invasive species, and should be continued in the future.

Acknowledgements

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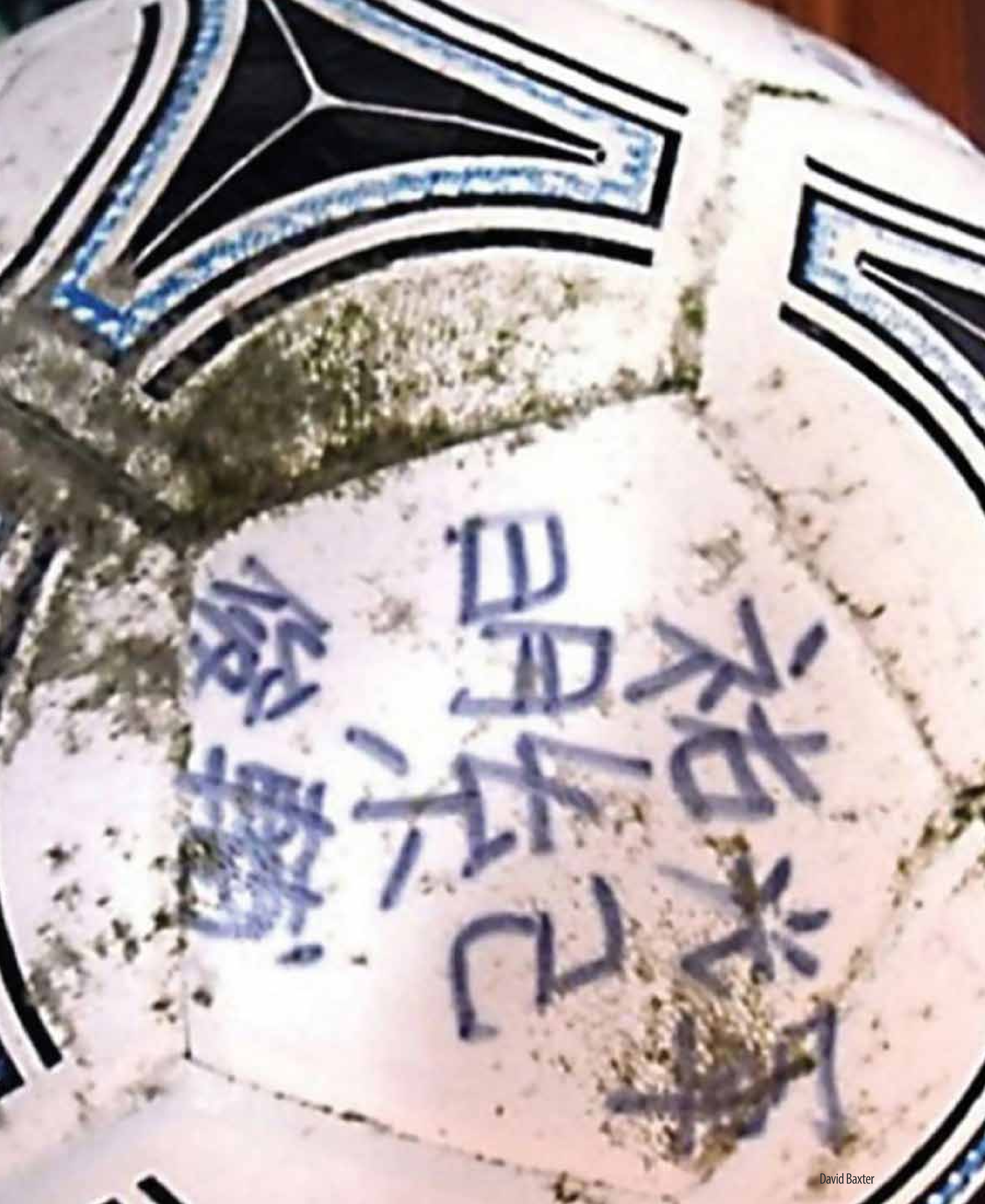

David Baxter

Chapter 3 Appendix

Appendix 3-1. Long-term monitoring of marine debris influx in Washington State

Appendix 3-1. Long-term monitoring of marine debris influx in Washington State

Supplementary Figure 3-1. Shoreline monitoring sites consecutively surveyed in northern Washington State, USA.

The indicator categories used by the National Marine Debris Monitoring Program (NMDMP; pre-2011) were compared to those used in the Marine Debris Monitoring and Assessment Project (MDMAP) protocol (post-2011). The MDMAP protocol aimed to record all debris items and so there are a larger number of debris categories. In the older NMDMP protocol, all debris was removed from the beach but only those debris items that fit into the pre-defined categories were recorded. In some categories, the item types were the same but had been given different names (e.g., metal beverage cans versus tin cans). New categories to MDMAP were removed from the counts. There were some categories in either protocol that were more finely described (e.g., rubber gloves and non-rubber gloves) and these were combined into the single category (e.g., gloves). A full description of the debris category comparison and combination is detailed in Supplementary Table 3-1.

Supplementary Table 3-1. Comparison of the pre-2011 (NMDMP) monitoring protocol and the post-2011 (MDMAP) protocol.

Pre-2011 category	Comparison	Post-2011 category
Balloons	=	Balloons
Condoms	combine →	Personal care products
Cotton swabs		Personal care products
Cruise line logo items	no	
Fish baskets	no	
Fishing line	=	Plastic/fishing lures and line
Floats/buoys	=	Plastic/buoys and floats
Gloves	←combine	Rubber/rubber gloves **and** cloth/fabric/gloves (non-rubber)
Light bulbs/tubes	no	
Light sticks	no	
Metal beverage cans	=	Metal/aluminum/tin cans
Motor oil containers (1 quart)	=	Plastic/other jugs/containers
Nets ^{3} 5 meshes	←combine	Plastic/plastic rope/net **and** cloth/fabric/rope/net pieces (non-nylon)
Oil/gas containers (> 1 quart)	=	Plastic/other jugs/containers
Pipe-thread protectors	No	
Plastic sheets ^{3} 1 m	No	Plastic
Plastic bags with seam < 1 m	combine	Plastic/bags
Plastic bags with seam ^{3} 1 m		Plastic/bags
Plastic bottles, beverage	=	Plastic/beverage bottles
Plastic bottles, bleach/clean	combine →	Plastic/other jugs/containers
Plastic bottles, food		Plastic/other jugs/containers
Plastic bottles, other plastic bottles		Plastic/other jugs/containers
Rope ^{3} 1 m	no	
Six-pack rings	=	Plastic/straws
Straps, closed	no	
Straps, open	no	
Straws	=	Plastic/straws
Syringes	combine →	Personal care products
Tampon applicators		Personal care products
Traps/pots	no	

"=" signifies equivalent categories, "no" indicates no equivalent, "combine" indicated finer resolution in either protocol, so the categories were summed together.

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THEME II – Arrival of Debris

Chapter 4: Webcam monitoring of marine and tsunami debris arrival in North America[1]

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Abstract

A webcam monitoring system was installed at a site overlooking a beach in Newport, Oregon, directly facing the North Pacific. The webcam was set up to sequentially and automatically take photographs of a part of the beach on which marine debris, including driftwood and anthropogenic debris (which might include Japanese Tsunami Marine Debris, JTMD) was littered. The arrival of marine debris was compared to local wind speeds. First, it seemed likely that the meridional wind component was responsible for the seasonal (summer to winter) increase of the debris abundance. It is likely that the shoreward Ekman transport carried marine debris toward the coast, and that the debris littered on the beach increased thereafter. Second, it is interesting that the marine debris decreased when the westerly (shoreward) winds prevailed in winter at spring tide. It is therefore reasonable to consider that the wind setup resulted in the re-drifting of debris during the westerly (shoreward) winds at spring tide (particularly at flood tide). A straightforward sub-model was constructed to reproduce the above-mentioned two critical factors. We combined the sub-model with a particle tracking model (PTM) reproducing JTMD motion in the North Pacific. Our estimates indicated that about 3% of JTMD was accumulated on the U.S. and Canadian beaches, and a large amount of JTMD has been washed ashore on the relatively narrow areas of Washington State and Oregon and the Central Coast of British Columbia and Vancouver Island.

Introduction

According to an estimate by the Ministry of the Environment, Government of Japan (MoE, 2011), about 5 million tons of Japanese Tsunami Marine Debris (JTMD) flowed into the North Pacific on March 11, 2011. Part of this JTMD (an estimated 1.5 million tons) remained afloat, and drifted in the North Pacific. This prompted concerns about the debris reaching the Pacific coast of North America and the Hawaiian Islands, which continues even at the present time. In particular, attention was focused on coastal Japanese species carried by JTMD because some of these species could have the potential to damage the indigenous marine ecosystem along the beaches of North America and the Hawaiian Islands (see Chapters 7 to 12).

However, it is a difficult task to estimate the abundance of JTMD (hence, the potential for invasive species) washed ashore on the coasts. To date, there have been no published studies investigating temporal variations of marine debris abundance on beaches along the Pacific U.S. and Canadian coasts over a period longer than one year (including seasonality), and with monitoring intervals shorter than a week. Consequently, there is no way of knowing the critical factors governing the temporal variations of debris abundance on these beaches. In this study, we installed a webcam system (originally described by Kako et al. (2010); Kataoka et al. (2012)) on a beach along the Pacific coast of the U.S. to hourly monitor the marine debris abundance over a 1-year period. Using this 1-year record, we then establish a numerical model to estimate the abundance of the JTMD washed ashore on the Pacific U.S. and Canadian coasts.

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[1] A reduced version of this chapter first appeared in PICES Press Vol. 25, No. 1, 2017. A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 33-43.

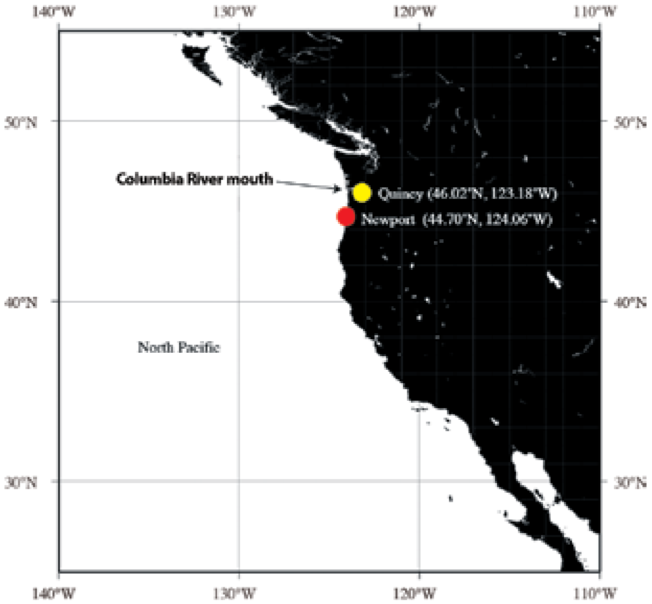

Figure 4-1. (Left) Map showing the locations of the webcam monitoring site (in Newport, Oregon) and the Quincy observatory, Washington (measures of river discharge) in relation to the Columbia River mouth and (above) photo of webcam system in place.

Methods

We installed a webcam overlooking a beach in Newport, Oregon, because this beach directly faced the North Pacific, was free from complex topography, and was easy to access (Figure 4-1). The webcam was set up to sequentially and automatically take photographs of a part of the beach on which marine debris, including driftwood and anthropogenic debris (which might include JTMD) was littered. Beach photographs were taken every 60 minutes during daytime (10 times from 9:00 a.m. to 6:00 p.m. Pacific Standard Time), beginning April 3, 2015. Analysis was conducted on photographs captured through to March 31, 2016. The area within the entire panorama measured approximately 60 m x 70 m in the alongshore and the offshore directions, respectively, and was photographed by the webcam with a fixed angle. These photographs were transmitted to our web server via the Internet, and had been opened publicly on our website during the ADRIFT project. In the study, the marine debris found on the beach was not separated into natural and anthropogenic debris because our objective was to establish the sub-model reproducing the critical factors to govern the abundance of the debris littered on the beach. Actual JTMD was difficult to identify from the photographs unless the debris source could be suggested by Japanese characters printed on the debris surface and those characters were sufficiently large to be identified on the photographs.

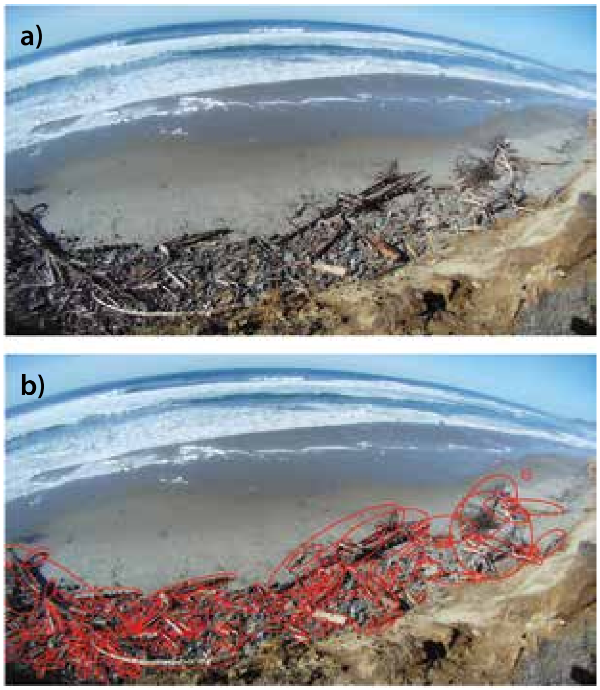

Figure 4-2. Webcam photographs of Newport Beach, Oregon on February 25, 2016. (a) Original photograph and (b) marine debris (surrounded by red circles) identified on the photograph by visual observation.

As shown in an example of photographs taken by the webcam (Figure 4-2a), it was found that substantial amounts of marine debris (mostly driftwood and lumber) were washed onto the beach over the 1-year period of monitoring. Thereafter, the abundance of marine debris was evaluated by counting the number of visible debris items in the beach photographs. First, an observer selected a single photograph from all 10 photographs taken on each day so as to identify the highest amounts of marine debris during the daytime. Thus, the photographs taken at ebb tide (i.e., the broadest beach area) were likely to be selected, whereas those taken during foggy and/or rainy periods were removed. Thereafter, the observer identified the marine debris regardless of the size, as shown in red circles in Figure 4-2b. If small objects were difficult to distinguish from shadows of surface irregularity on the beach, the remaining nine photographs taken at different times (different incident angles of the sunlight) were used to confirm the identification. To reduce human error in counting the marine debris, visual observations were conducted twice by different observers to double-check the omissions and/or duplications of the marine debris.

The abundance of marine debris littered on the beaches was evaluated by ratios of the marine debris areas projected on a horizontal plane to that of the beach (hereinafter referred to as "percent cover"). The procedures of image processing described below were based on Kataoka et al. (2012), where areas covered by anthropogenic plastic debris were computed using images taken by webcams installed on Japanese beaches. First, they defined a range of colors for anthropogenic plastic debris on a CIELUV color space (hereinafter, the range is referred to as "color reference"). Second, the pixels of marine debris (hereinafter, "debris pixel") were extracted from the webcam-derived images by computing the Euclidean distance on the color space between background (natural things such as sand and driftwood) and the anthropogenic debris defined by the predetermined color reference. Third, the extracted images were then converted to those on a geographic (Cartesian) coordinate, that is, images to which our sight line is perpendicular, by applying a projective transformation method (i.e., georeferencing described by Kako et al. (2010)), otherwise the photographs are distorted and thus, are unsuitable for accurately computing the areas covered by marine debris. Last, areas of marine debris were calculated by multiplying the number of the debris pixels by the area of a single pixel (0.01 m^2 in the present application) determined uniquely by the projective transformation method (Kako et al., 2010). From the size of a single pixel, we can evaluate the amount of marine macro-debris larger than 0.01 m^2 of projected area.

The temporal variation of the marine debris numbers counted on the beach was compared with that of satellite-derived wind data to investigate the potential causes(s) of the variation. We used a global gridded wind vector dataset constructed by applying an optimum interpolation method (Kako et al., 2011) to the Level 2.0 Advanced Scatterometer (ASCAT) wind product (Verspeek et al., 2009).

A straightforward model was constructed to validate whether or not coastal upwelling/downwelling and wind setup determine the variation of marine debris abundance on the beach. We assumed that the marine debris abundance (N) on the beach depended on the meridional (V) and zonal (U) wind directions at grid cell nearest to Newport. The abundance increased by 1 when southerly winds occurred ($N = N + 1$ at $V > 0$; coastal downwelling) while the debris abundance on the beach decreased when the shoreward wind speed became higher than its temporal average at spring tide ($N \rightarrow 0$ at $U >$ average over the entire period; wind setup). The variation in marine debris abundance over time at the single webcam system location was then extrapolated to a larger area using the results from the British Columbia aerial surveys and image analysis (see Chapter 5; Kataoka et al., 2018).

Results and Discussion

The meridional wind component was responsible for the seasonal (summer to winter) increase of debris abundance. In fact, the seasonal increase was revealed when southerly winds prevailed because of the development of the Aleutian low over the North Pacific; this can be observed through comparison of the two linear trends between September and March in Figure 4-3a. The seasonal increase of the marine debris during southerly winds suggests the dependence of the debris abundance on the occurrence of coastal upwelling/downwelling and its associated cross-shore Ekman flows. In fact, it is well known that coastal upwelling occurs along the Pacific coast of North America, especially during the summer, and downwelling prevails in winter (Duxbury et al., 2002). When the southerly (downwelling-favorable) winds prevail, it is likely that the shoreward Ekman transport carried marine debris toward the coast, and that the debris littered on the beach subsequently increased. Meanwhile, the beach litter decreased when drifting marine debris was prevented from approaching the coast because of the offshoreward Ekman transport induced by the northerly (upwelling-favorable) winds.

The sub-monthly fluctuations of debris abundance (Figure 4-3) superimposed on the seasonal increase appear to be related to fluctuations in the zonal wind component, especially in the latter half of the study period (from the mid-October to the end; Figure 4-3b). It is interesting that marine debris decreased when the westerly (shoreward) winds prevailed in winter. One may consider that the debris abundance varied in a non-intuitive manner because shoreward winds were likely to carry floating objects onto the beach owing to wind-induced surface currents and leeway drift. It should be noted that the minimal abundance in the latter half of the study period appeared when westerly winds prevailed at spring tides (grey bars in Figure 4-3b).

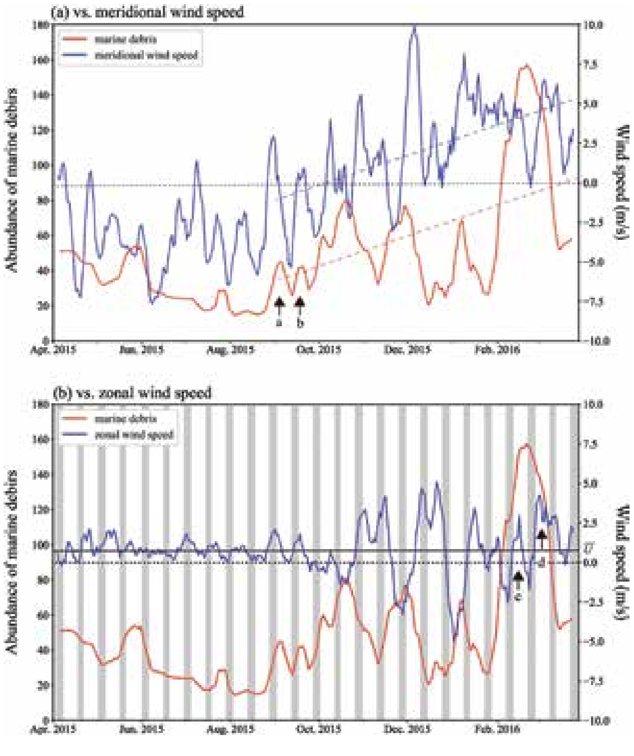

Figure 4-3. Comparison of marine debris abundance (red) with wind speed components (blue) (7-day running mean). The debris abundance is depicted in relation to the (a) meridional wind speed and (b) zonal wind speed. Grey bars in panel b indicate the period of the spring tides.

Figure 4-4. Photographs of the day before (top, December 9, 2015), during (middle, December 11), and after (bottom, December 13) the westerly winds prevailed at the spring tide. The change of the ground form just below the webcam resulted from the land slide that occurred due to a storm on December 11.

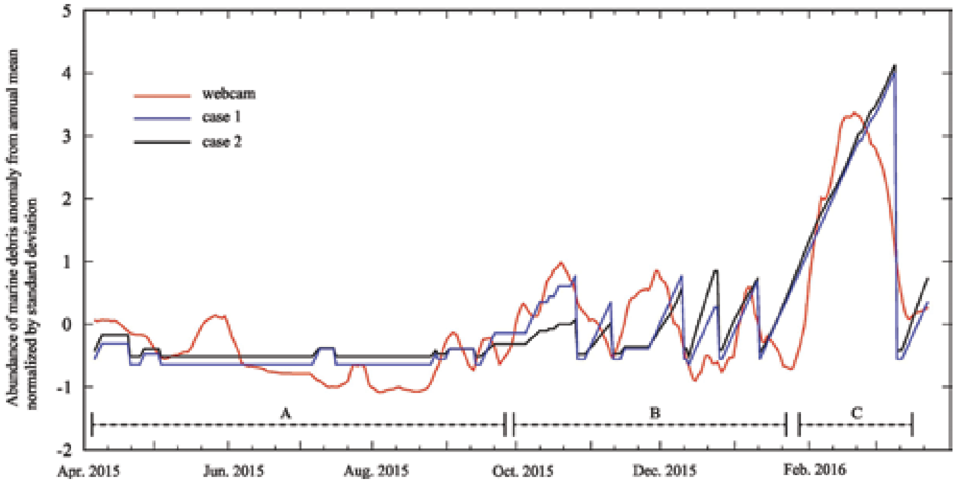

Figure 4-5. Time series of abundance of the webcam-observed (red) and modeled (blue) marine debris. (Case 2 (black) was not used in this report).

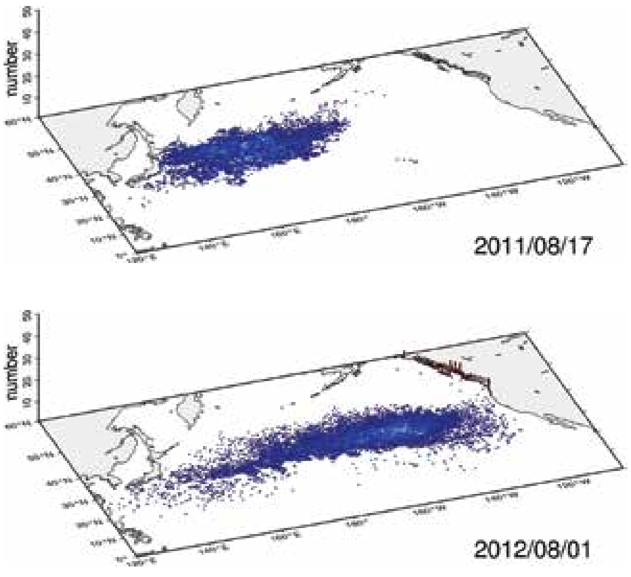

Figure 4-6. Two snapshots of the Particle Tracking Model (PTM) combined with the sub-model.

It is therefore reasonable to consider that the wind setup resulted in the re-drifting of debris during the westerly (shoreward) winds at spring tide (particularly at flood tide). The photograph of the beach on December 11, 2015, when the westerly wind prevailed at the first spring tide, showed that the high-tide line moved landward over the entire beach (Figure 4-4, middle). Thus, it is likely that the seawater occupied the entire beach mostly "swept" the marine debris (December 13; Figure 4-4, bottom), which had been accumulated on the beach until the occurrence of the wind setup (Figure 4-4, top).

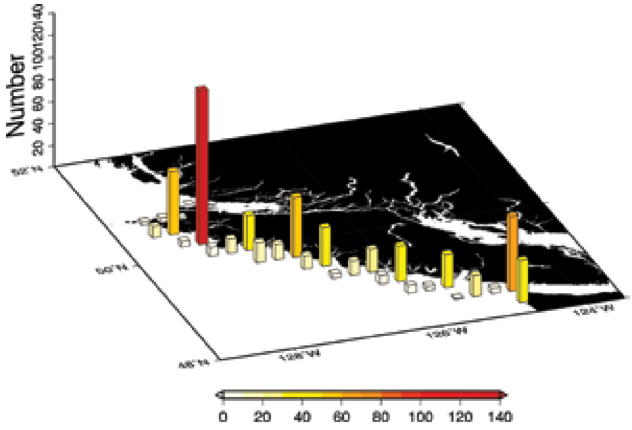

Figure 4-7. Modeled particle abundance averaged on the same day of an aerial photography survey in Figure 4-3.

Model of marine debris arrival

In spite of its simplicity, the model did a reasonable job of reproducing the abundance of marine debris on the beach (Figure 4-5). The correlation coefficient between the webcam observation and the model run was 0.85, significant at the 99% confidence level. It is anticipated that the model is capable of reproducing the marine debris abundance on various beaches along the U.S. and Canadian Pacific coasts because it is free of Newport Beach-specific factors, and because the coastal upwelling/downwelling and the wind setup at spring tides occurs across the Pacific coasts of North America.

We then combined the above "sub-model" with a Particle Tracking Model (PTM) reproducing JTMD motion in the North Pacific. The sub-model gives the criterion whether modeled particles approaching coasts are washed ashore on the land grid cell, and whether they return to the oceanic domain from the land. The satellite-derived winds on the oceanic grid cells neighboring the land boundary were used for calculation in the sub-model. The PTM used surface ocean

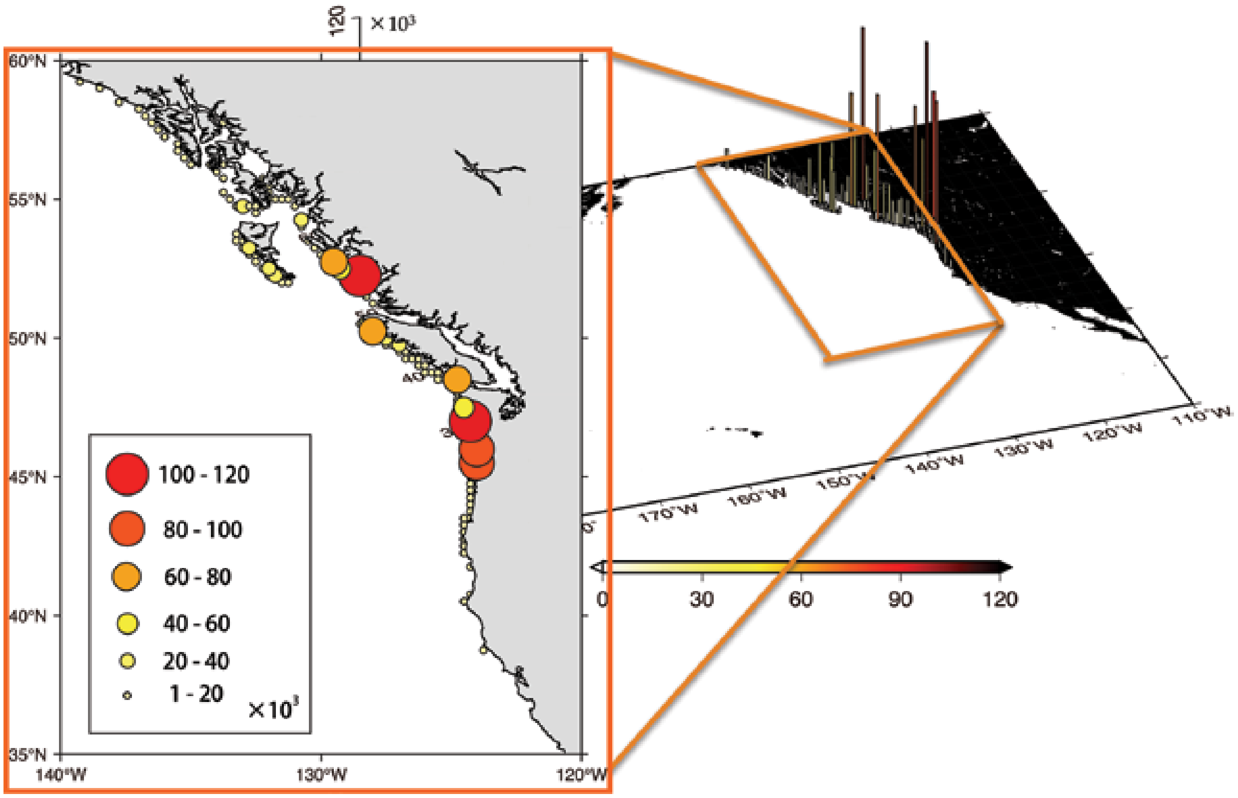

Figure 4-8. Particle abundance integrated over a 5-year computational period. Particle numbers washed ashore on the beach grid cells are represented by the bar height, and are also represented by circle diameters in the enlarged map in the left panel.

currents provided by the HYCOM[2], and ASCAT winds were used for both the PTM and sub-model. Fifty thousand model particles were released off the Sanriku coast, Japan, on March 11, 2011, after which a 5-year computation was conducted. An advantage of combining the sub-model with PTM over the conventional PTM is demonstrated in Figure 4-6, where the abundance of particles washed ashore was computed on the beaches as well as particles carried in the ocean. It should be noted that the abundance of modeled particles on Vancouver Island became larger in the north than that in the south. This pattern is consistent with the results of aerial photography (see Chapter 5), and validated the capability of the combination of PTM and sub-model to compute the abundance of JTMD actually washed onto the beach (Figure 4-7).

In summary, the abundance integrated over the 5 years (Figure 4-8) demonstrated that JTMD has not washed ashore homogeneously on the entire Pacific coast of the U.S. and Canada. Indeed, JTMD has been found from northern California to Alaska (see Chapter 3). It was however, suggested that large amounts of JTMD have washed ashore on the relatively narrow areas (<1000 km) around Washington State, Oregon and the Central Coast of British Columbia, which might act as a "gateway" for invasive species carried by JTMD.

Conclusions

This was the first installation of a webcam monitoring system in the U.S. and there was extensive support from colleagues in Newport. To evaluate the potential for marine debris and potential invasive species to be washed ashore on the U.S. and Canadian coasts, we estimated where and how much marine debris, and therefore JTMD, could have washed ashore. Based on webcam monitoring, aerial photography, and Particle Tracking Model experiments, we estimated that about 3% of JTMD could have accumulated on U.S. and Canadian beaches, and large amounts of JTMD were likely to have washed ashore on the relatively narrow areas around Oregon and Washington State, and Vancouver Island and Central Coast of British Columbia.

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[2] https://hycom.org

Acknowledgements

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Chapter 5: Surveillance of debris in British Columbia, Canada[1]

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Abstract

The abundance of marine macro-debris was quantified with high spatial resolution by applying an image processing technique to archived shoreline aerial photographs taken over Vancouver Island, Canada. The photographs taken from an airplane at oblique angles were processed by projective transformation for georeferencing, where five reference points were defined by comparing aerial photographs with satellite images of Google Earth. Thereafter, pixels of marine debris were extracted based on their color differences from the background beaches. The debris abundance can be evaluated by a ratio of an area covered by marine debris to that of the beach (percent cover). The horizontal distribution of percent cover of marine debris was successfully computed by applying the image processing to 167 aerial photographs and was significantly related to offshore Ekman flows and winds (leeway drift and Stokes drift). Therefore, the estimated percent cover was useful information to determine priority sites for mitigation, cleanup efforts, and monitoring for assessing adverse impacts.

Introduction

Marine debris has become a significant concern for the health of the ocean and is increasing in magnitude. Marine debris has had adverse impacts on pelagic and coastal ecosystems and the various ecosystem services they provide (Gall and Thompson, 2015). The primary impact of marine debris on marine mammals, turtles, and birds through entanglement and ingestion is well documented (Laist, 1997; Gall and Thompson, 2015), and the impact of microplastics, which are plastics smaller than 5 mm diameter, on marine ecosystems has become an emerging problem (Andrady, 2011; Wright et al., 2013). In addition, marine debris provides new habitat and facilitates the transport of invasive species (Gall and Thompson, 2015), as highlighted by the transport of coastal Japanese species to North America by debris from the Great Japan Tsunami of 2011.

Evaluating the abundance of marine macro-debris (> 20 mm diameter; Barnes et al., 2009) on beaches (hereinafter referred to as “debris abundance”) is one of the key factors for assessing these adverse impacts on the marine environment and/or ecosystems (Barnes et al., 2009). Debris abundance is most visible and noticeable on shorelines where it washes up and has been documented throughout the North Pacific: the United States Pacific Coast and Hawaii (Ribic et al., 2012), northern Japan (Goto and Shibata, 2015), northwestern Hawaiian Islands (Morishige et al., 2007), and Maui, Hawaii (Blickley et al., 2016). Debris abundance does not increase monotonically on a beach (Kako et al., 2010), but varies temporally with re-drifting from the beach to the oceans. Nearshore hydrodynamic processes such as wave setup are known to wash debris offshore (Kataoka et al., 2013, 2015). Owing to this backwash process, we have to recognize that the beaches are not only receptors of marine debris, but also secondary sources of marine debris in the marine environment. Hence, in addition to preserving the aesthetic and tourism value of beaches, beach cleanup activities are capable of preventing marine debris from re-entering the ocean from these secondary sources. Furthermore, quantifying debris abundance to identify accumulated areas can assist in the prioritization and allocation of cleanup activities to remove debris efficiently from marine environments.

A number of methods have been developed to quantify the debris abundance on shorelines (e.g., Kako et al., 2010; Kataoka et al., 2012; Veenstra and Churnside, 2012; Ge et al., 2016). Beach surveys, often conducted by volunteer community groups, are highly accurate measures of debris abundance (Opfer et al., 2012) but are limited in spatial scope to accessible, individual beaches. Aerial surveys using fixed-wing planes are useful tools to search and document long stretches of inaccessible coastlines in order to identify large debris items or specific debris types, to estimate the relative abundance of debris, and to prioritize areas for debris cleanup (Veenstra and Churnside, 2012). Although these surveys can widely cover remote areas quickly and relatively easily, their measurement accuracy should be evaluated through ground-truth survey techniques. Meanwhile, an alternative method for remotely monitoring

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[1] A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 44-51.

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the debris abundance is the usage of a webcam (Kako et al., 2010; Kataoka et al., 2012), where image analysis techniques are applied to webcam images to sequentially quantify debris abundance on specific beaches (see Chapter 4). These techniques can be automated, making the technique more efficient and low cost, although webcam monitoring also requires ground-truth data to validate the observed area. The application of image analysis techniques to aerial (webcam) photographs (see Chapter 4)may allow us to quantify the debris abundance with high spatial (temporal) resolution over a wide area (long period). Recently, a novel technique for quantifying debris abundance using light detection and ranging (LIDAR) technology has been developed (Ge et al., 2016). This technique can classify and quantify marine debris based on its shape by applying image processing regardless of sunlight condition, although LIDAR sensors are rare and expensive which would make it difficult to employ over a wide area. Aerial photographic surveys using a digital camera have been carried out along the western coast of North America (Alaska, USA, and British Columbia, Canada). Quantification of the marine debris in these archived aerial photographs would enable us to efficiently understand the debris abundance over a wide area with little additional cost.

Here, we attempt to develop an image analysis technique for quantifying the debris abundance from these archived aerial photographs. The debris abundance was computed for a study area around Vancouver Island (because of the intensive accumulation of debris as shown later) located southwest of British Columbia, Canada (Figure 5-1a). To date, the debris abundance has been evaluated in line with a subjective and visual analysis by an observer in the aerial photography (e.g., six ranks of debris coverage over beaches, shown in Table 5-1). However, this relative abundance might vary by observers, and by altitudes and camera angles of the aerial photography. In the present study, however, area of beach covered by marine debris is computed objectively and used to estimate the abundance of debris washed ashore on beaches. These estimates can be used, for instance, to assess the cost of beach cleanup and prioritize debris accumulation hot spots. Furthermore, we investigate which factors determine the debris accumulation patterns around Vancouver Island by comparing with ocean currents and winds. Finally, we outline and compare requirements to conduct debris monitoring and cleanup activities appropriately and effectively.

Data and Methods

Aerial photography survey

Aerial surveys were conducted on the west coast of Vancouver Island (October 7 and December 3, 2014) and the central coast of British Columbia and Haida Gwaii (January 30 and March 2, 2015) as parts of the Assessing the Debris-Related Impact From the Tsunami (ADRIFT) project, which started to assess the risk of invasive species carried by Japanese Tsunami Marine Debris (JTMD) to North American and Hawaiian coastal ecosystems. The aerial surveys have covered more than 1,500 km of British Columbia's coastline, and provided us with 6,228 photographs on the west coast of British Columbia (Figure 5-1b). In these surveys, oblique aerial photographs had been taken by a camera (single-lens reflex digital camera with 24.3 megapixels of effective pixels, D750, Nikon) from a small fixed-wing airplane flying between 500 and 1000 m above the beaches. Since the camera was not fixed to the airplane, the exposure angles were varied in different photographs. The flight track and altitude were recorded with a built-in GPS device over the course of the aerial photography survey.

Prior to the image analysis, all 6,228 aerial photographs were first categorized into six "debris rankings" based on the debris density, the definition of which is described in Table 5-1. The debris rankings of aerial photographs were all spatially averaged based on those photographing locations along segments with a length of 1 km (Figure 5-1b). The debris ranking of segments can be viewed publicly [2].

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[2] http://www.arcgis.com/home/webmap/viewer.html?webmap=3c5fb88b7f3f4d97974615acad67af3e

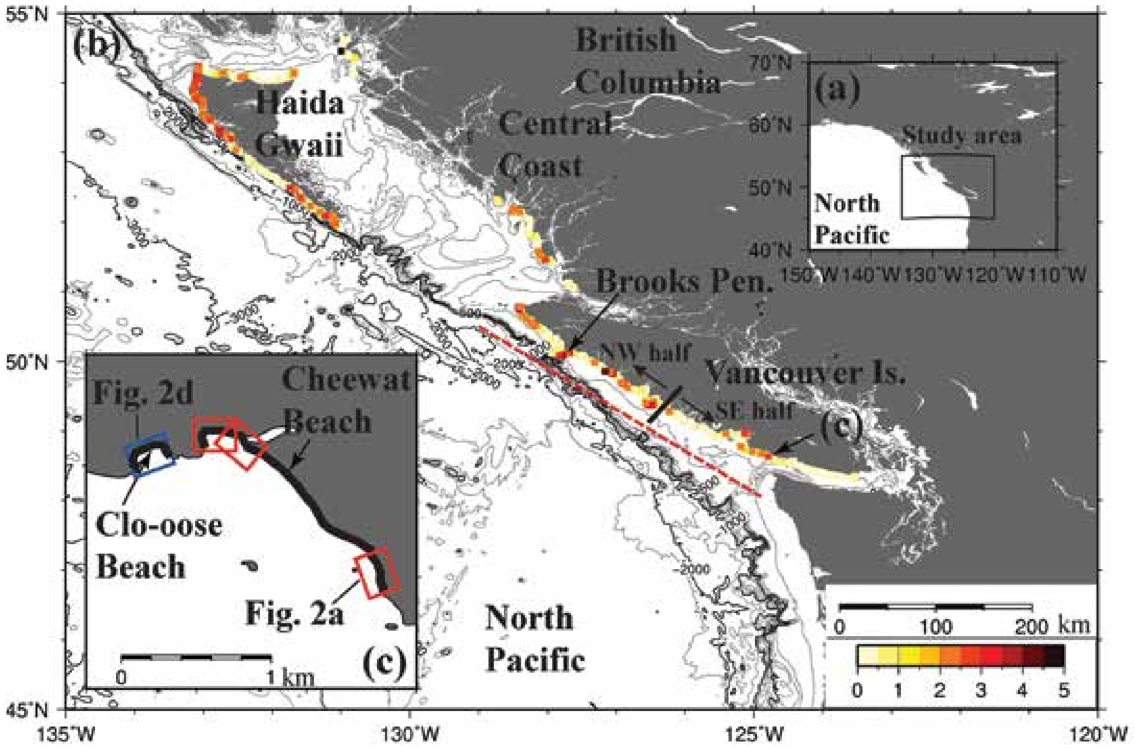

Figure 5-1. Study area. (a) Location of the west coast of British Columbia, Canada (box). (b) Enlarged map of the study area. The western coastline of Vancouver Island is divided into the southeastern (SE) half and northwestern (NW) half by a bold line. Contour lines denote the isobaths in meters, and the red broken line is set for calculating the mean current/wind speed shown in Figure 5-5. The yellow–red gradation denotes the debris rankings determined visually by observers of the aerial survey. Its color scale is shown in the lower right of panel (b). (c) The locations of Cloo-oose Beach and Cheewat Beach where the shoreline in-situ survey was conducted on July 28, 2015. The red (blue) boxes denote the coverage of the aerial photographs on Cheewat (Cloo-oose) Beach where we estimated the percent cover.

Table 5-1. Descriptions of debris rankings observed visually in aerial photographs.

Debris ranking	Description
0 (unranked)	No visible debris in image, not including logs
1	Single piece of debris visible, not including logs
2	More than one piece of visible debris, not including logs
3	Several pieces of visible debris (> 5) covering beach area of image, not including logs
4	Significant debris on beach area or in pockets of beach with a variety of visible debris types, not including logs
5	Significant debris evenly distributed over an entire beach area with multiple debris types visible, not including logs


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Image processing and subsequent analyses

The abundance of marine debris littered on the beaches was evaluated by ratios of the marine debris areas projected on a horizontal plane to that of the beach (hereinafter referred to as "percent cover"). The procedures of image processing described below are based on Kataoka et al. (2012) where areas covered by anthropogenic plastic debris were computed using images taken by webcams installed on Japanese beaches. First, they defined a range of colors for anthropogenic plastic debris on a CIELUV color space (hereinafter, the range is referred to as "color reference"). Second, the pixels of marine debris (hereinafter, "debris pixel") were extracted from the webcam-derived images by computing the Euclidean distance on the color space between background (natural things such as sand and driftwood) and the anthropogenic debris defined by the predetermined color reference. However, it should be noted that, in general, the coverage of aerial photographs depends on both flight altitudes and exposure angles. Third, the extracted images were converted to those on a geographic (Cartesian) coordinate, that is, images to which our sight line is perpendicular, by applying a projective transformation method (i.e., georeferencing described in Kako et al. (2012)); otherwise the aerial photographs are originally distorted, and thus, they are unsuitable for accurately computing the areas covered by marine debris. According to Kako et al. (2012), the geometric relationship between geographic coordinates (X, Y) on the beach surfaces and photographic coordinates (x, y) is represented as:

$$X = \frac{b_1 x + b_2 y + b_3}{b_4 x + b_5 y + 1}, \quad Y = \frac{c_1 x + c_2 y + c_3}{c_4 x + c_5 y + 1} \qquad (1)$$

where b_i and c_i ($i = 1, 2, ..., 5$) represent the coefficients for rotating the photograph in both horizontal and vertical directions to the Cartesian plane. If the GPS-derived geographic positions of four reference points (i.e., eight values by a combination of x and y), at least, are available within the aerial photographs, we can determine the coefficients in Eq. (1) by applying a least square method; note that 10 unknown coefficients in Eq. (1) can be reduced to eight coefficients because of $b_4 = c_4$ and $b_5 = c_5$ in the present application (Kako et al., 2012). Last, areas of marine debris were calculated by multiplying the number of the debris pixels by the area of a single pixel (0.01 m^2 in the present application) determined uniquely by the projective transformation method (Kako et al., 2012). Last, areas of marine debris were calculated by multiplying the number of the debris pixels by the area of a single pixel (0.01 m^2 in the present application) determined uniquely by the projective transformation method (Kako et al., 2012). It should be noted that the area of a single pixel (= 0.1 m x 0.1 m) was predetermined before georeferencing, and therafter the coefficients b_i and c_i in Eq. (1) were determined in georeferencing so as to give the X-Y field with the spatial resolution of 0.01 m^2. From the size of a single pixel, we can evaluate the amount of marine macro-debris larger than 0.01 m^2 of projected area.

The procedures mentioned above were applied to the aerial photographs taken over the British Columbia coasts, on which large quantities of logs and lumber were washed ashore in addition to the anthropogenic debris. The color references were determined first to avoid the extraction of the non-debris pixels from the aerial photographs. In the present application the color of debris pixel is represented with the values (v) of three primary colors (red, green and blue: RGB). The average ($\bar{v}$) and standard deviation (σ) calculated from the RGB values of debris pixels are used as color references through trial and error. Namely, if each RGB value of a pixel is included within $\bar{v} \pm \sigma$, it can be determined as the debris pixel. On the British Columbia coasts, a difficulty for the projective transformation arises from the fact that reference points could not be physically set owing to the inaccessibility of the beaches. Thus, in lieu of setting the physical reference points, we used satellite images provided by Google Earth. The satellite images of Google Earth have been already geometrically corrected (i.e., ortho-corrected), and thus, the reference points with both latitude and longitude data can be chosen arbitrarily from the satellite image. Geographic markers such as headlands, rocks, and trees that could be identified on both the satellite image and the aerial photograph were used as reference points. In general, reference points are difficult to assign to sandy beaches because of the shoreline rapidly moving by tides and waves, unless immobile objects such as rocks are identified in the aerial photographs. In the present study, five reference points corresponding to immobile objects (not four points, to enhance the accuracy) were carefully selected in the aerial photographs through the comparison between the aerial photograph and satellite image of Google Earth.

Shoreline in-situ surveys

To validate the percent cover estimated using the aerial photographs, we simultaneously carried out shoreline in-situ surveys along with the aerial photography on Cheewat Beach and Cloo-oose Beach located on the southwestern coast of Vancouver Island on July 28–29, 2015 (Figure 5-1c). The dimensions of Cheewat and Cloo-oose beaches are approximately 98 m wide x 1.9 km long and 49 m wide x 0.19 km long, respectively. The numbers of marine debris per unit area (hereinafter, "surface number density") on these beaches were measured by volunteer groups following the National Oceanic and Atmospheric Administration (NOAA) Shoreline Monitoring Protocol (Opfer et al., 2012). In the shoreline in-situ survey, the number of anthropogenic debris items such as plastics, beverage bottles, cans, disposable lighters, floats and lumber was recorded, and the debris removed from the beaches. The surface number density was computed by using their number and area of each beach.

Ocean current and sea wind data

To examine the factors that affect debris accumulation, we focused on the spatio-temporal variation of the ocean surface currents and sea winds west of the British Columbia coast (135°–120°W and 45°–55°N; see Figure 5-1b) over the course of 2014. In addition to the horizontal maps of ocean currents and winds, time series of both the surface current velocity and sea wind averaged over a line of Vancouver Island (i.e., red broken line in Figure 5-1b) were investigated. We used ocean current data calculated by the Hybrid Coordinate Ocean Model (HYCOM) and sea wind gridded data from Advanced Scatterometer (ASCAT) observations. Since the details of HYCOM and ASCAT gridded data are described by Chassignet et al. (2007) and Kako et al. (2011), respectively, only a brief description of the HYCOM model and ASCAT data is included here. The HYCOM provides us with global daily current data with a grid spacing of $1/12°$ on the native Mercator-curvilinear horizontal grid and 33 vertical levels from September 19, 2008 to the present. In the study, the zonal (u) and meridional (v) current velocities in the uppermost layer ($z = 0.0$ m) downloaded from http://hycom.org were used. Kako et al. (2011) provided global daily sea–wind vector data with a grid spacing of ¼° by applying an optimum interpolation method to ASCAT data. These gridded ASCAT data can be downloaded from http://mepl1.riam.kyushu-u.ac.jp/~kako/ASCAT/NetCDF/.

Results

Validation of the percent cover estimated from aerial photographs

To compare the percent cover in the aerial photographs with the surface number densities observed by the in-situ surveys on Cheewat and Cloo-oose beaches (Figure 5-1c), the photographs taken on these beaches were processed. Let us demonstrate the case of the original aerial photograph taken over the southern part of Cheewat Beach as an example (the red box in Figure 5-1c is shown in Figure 5-2a); note that this long-distance beach was divided into eleven parts for the aerial photography. The original photograph was converted to an image on the Cartesian coordinate (i.e., projective transformation; Figure 5-2b) by substituting the photographic coordinates into Eq. (1), including the coefficients obtained in a least square sense using the positions of five reference points on both a satellite map and original photograph (Figure 5-2a).

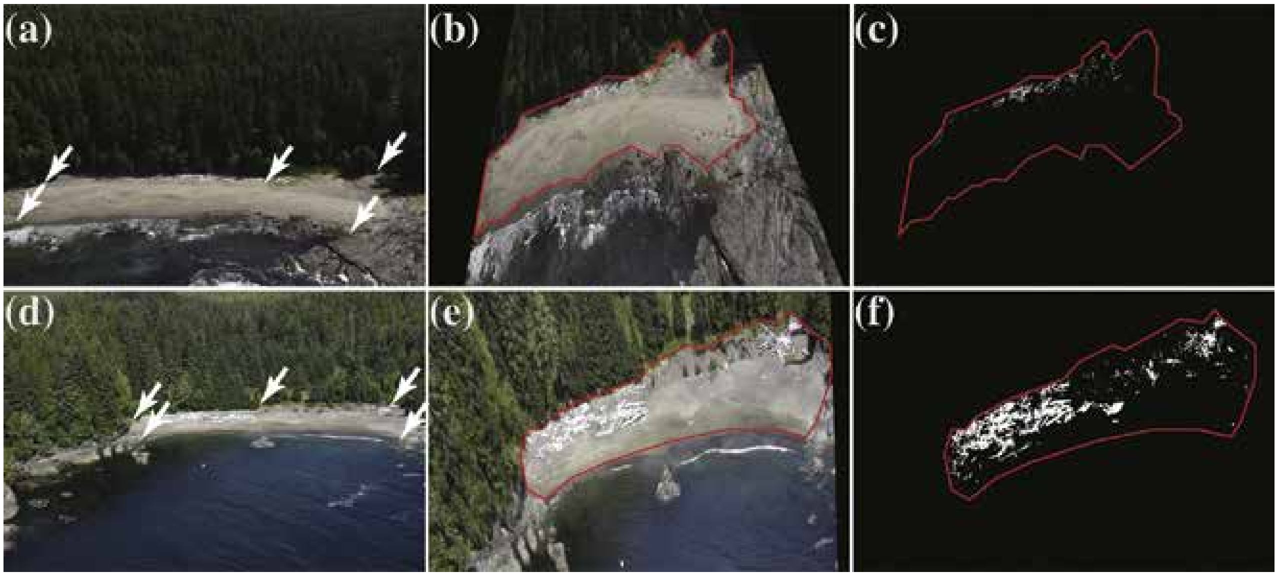


Figure 5-2. Image processing to (a, b, and c) Cheewat Beach and (d, e, and f) Cloo-oose Beach. (a) and (d) Original photographs taken by aerial survey. White arrows denote the five reference points required for the projective transformation. (b) and (e) The projective transformation method was applied to the images (a) and (d). (c) and (f) The pixels of marine debris shown in white were extracted by image processing as described in the text. Red outlines in the images (b), (c), (e) and (f) denote the beach areas defined to compute the percent cover.

The outer boundary of the beach was determined in the processed image by visual examination (red outline in Figure 5-2b). The accuracy of the projective transformation was estimated by comparing the "true" positions of five reference points on the satellite map with those on the processed image, resulting in an error estimate of < 1%. Thereafter, by using the color references, the debris pixels were extracted from the converted images (see white dots in Figure 5-2c). The area covered by marine debris in the example image was estimated to be 98 m^2 by multiplying the total number of debris pixels (9,764 pixels) on the converted image with the area of the single pixel (0.01 m^2; Figure 5-2c). Last, the percent cover of one of the photographs of Cheewat Beach (Figure 5-2a) can be estimated to 1% by taking a ratio of the area covered by marine debris (98 m^2) to the area of beach (8,124 m^2). The same image processing was applied to the photograph of Cloo-oose Beach (Figure 5-2d, e, and f), and the resultant percent cover was 14%.

The percent cover estimated from the aerial photographs was consistent with surface number densities measured by the shoreline in-situ survey (Table 5-2). The percent cover on Cloo-oose Beach was estimated using a single aerial photograph of the entire beach (blue box in Figure 5-1c), while the percent cover on Cheewat Beach was computed using three aerial photographs of the northern and southern parts of the beach (red boxes in Figure 5-1c). Although we had taken eleven photographs of Cheewat Beach in total, only three photographs were available for the projective transformation because of a lack of the appropriate five reference points in the remaining eight photographs. The estimated percent cover of Cloo-oose Beach is 14%, which is 3.5 times larger than that of Cheewat Beach (4%). The surface number densities on these two beaches were 0.049 and 0.014 items m^{-2}, respectively, the ratio of which was also 3½ times larger (Table 5-2). Hence, the estimate of percent cover would be reasonable to estimate the abundance of debris littered on the actual beaches.

Accumulation of marine debris on Vancouver Island

The debris ranking shown in Figure 5-1b by colored dots indicates that the visible debris was relatively low along the shorelines of British Columbia. Nonetheless, the debris abundance seems to be highest at the northwest corners of Haida Gwaii and Vancouver Island (Figure 5-1b). Among all aerial photographs of British Columbia's coast, the photographs of Vancouver Island, including the 1-km segments with debris ranking larger than 1 (167 photographs in total) were selected to apply the aforementioned image processing in the subsequent analyses because the shoreline in-situ surveys were conducted in the same area (Figure 5-1c).

The map of percent cover estimated from 167 photographs (Figure 5-3) was roughly, but not exactly, the same as that of the debris ranking (Figure 5-1b). Here, we divided the western coastline of Vancouver Island by a bold line; see Figure 5-1b and Figure 5-3. We found that both the debris ranking (Figure 5-1b) and percent cover (Figure 5-3) in the northwestern half of the coastline are higher than those in the southeastern half. However, the highest percent cover of 38% was found around the northern tip of Vancouver Island, although the highest debris ranking (4-5) was found southeast of Brooks Peninsula further south (Figure 5-1b). Relatively high debris ranking (approximately 3) was detected around the Cloo-oose and Cheewat beaches (Figure 5-1c) despite the moderate (< 20%) percent cover in the same area (Figure 5-3). The beach aspects within photographs are mostly southward (40%) or southwestward (45%) (Figure 5-4a). However, it is interesting to note that the percent cover averaged over beaches in each aspect was nearly the same (8–10%) in regard to the beaches with aspect from westward to southeastward (Figure 5-4b).

Table 5-2. Comparison between the estimated percent cover and surface number densities on Cloo-oose and Cheewat beaches.

Beach	Percent cover (%)	Surface number density (items m^{-2})
Cheewat Beach	4	0.014
Cloo-oose Beach	14	0.049

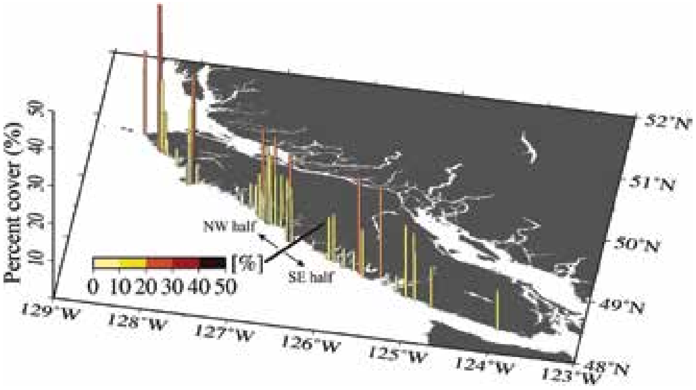
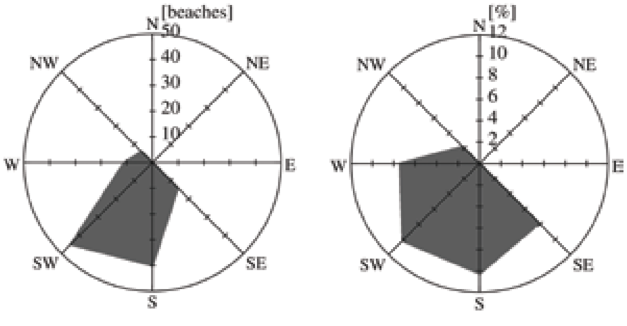


Figure 5-3. Horizontal distribution of percent cover estimated by applying our image processing to the aerial photographs taken on Vancouver Island. The yellow–red gradation represents the percent cover, the color scale of which is shown in the lower left of the panel. The western coastline of Vancouver Island is divided into the southeastern (SE) half and northwestern (NW) half by a bold line.



(a) Number of beaches (b) Mean percent cover

Figure 5-4. Frequency maps of (a) the number of beaches facing each direction, for which percent covers were calculated and (b) the percent covers averaged over beaches in each aspect.

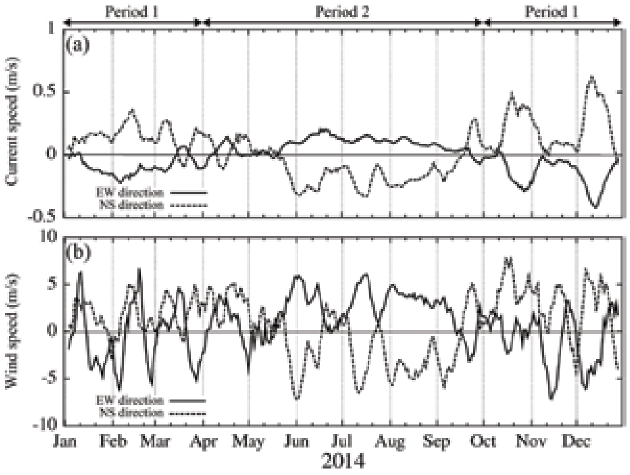


Figure 5-5. Time series of a 7-day moving average of currents (a) and wind speeds (b) averaged over the red broken line in Figure 5-1b in 2014. In both panels, the solid and broken curves represent the time series of zonal (i.e., east–west) and meridional (i.e., north–south) components, respectively. The positive values in zonal and meridional components denote the eastward and northward current/wind speeds, respectively.

Current and wind patterns off Vancouver Island

The dependence of debris abundance on both ocean currents and sea winds off Vancouver Island is likely to be significant, and thus, we investigated the spatio-temporal patterns of the ocean surface currents and sea winds west of the British Columbia coast using the HYCOM and ASCAT data. Both ocean surface currents and sea winds showed a remarkable seasonality. The surface current velocities off Vancouver Island were smoothed by a 7-day moving average to remove the short-term fluctuations owing to the passing of extratropical cyclones (Figure 5-5a). The northwestward currents were predominant in fall and winter (from October to March; hereinafter "period 1"; see Figure 5-5), while the southeastward currents prevailed in spring and summer (from April to September; hereinafter "period 2"; see Figure 5-5). Similarly, the sea-wind speeds also varied seasonally (Figure 5-5b). In period 1, the northwestward wind component seemed to prevail in addition to the intra-seasonal fluctuations. Thereafter, the sea-wind direction shifted to the southeast over the course of period 2. The seasonal variability of sea-wind direction coincided with that of the surface currents, and thus, the occurrence of the coastal boundary currents driven by winds is suggested.

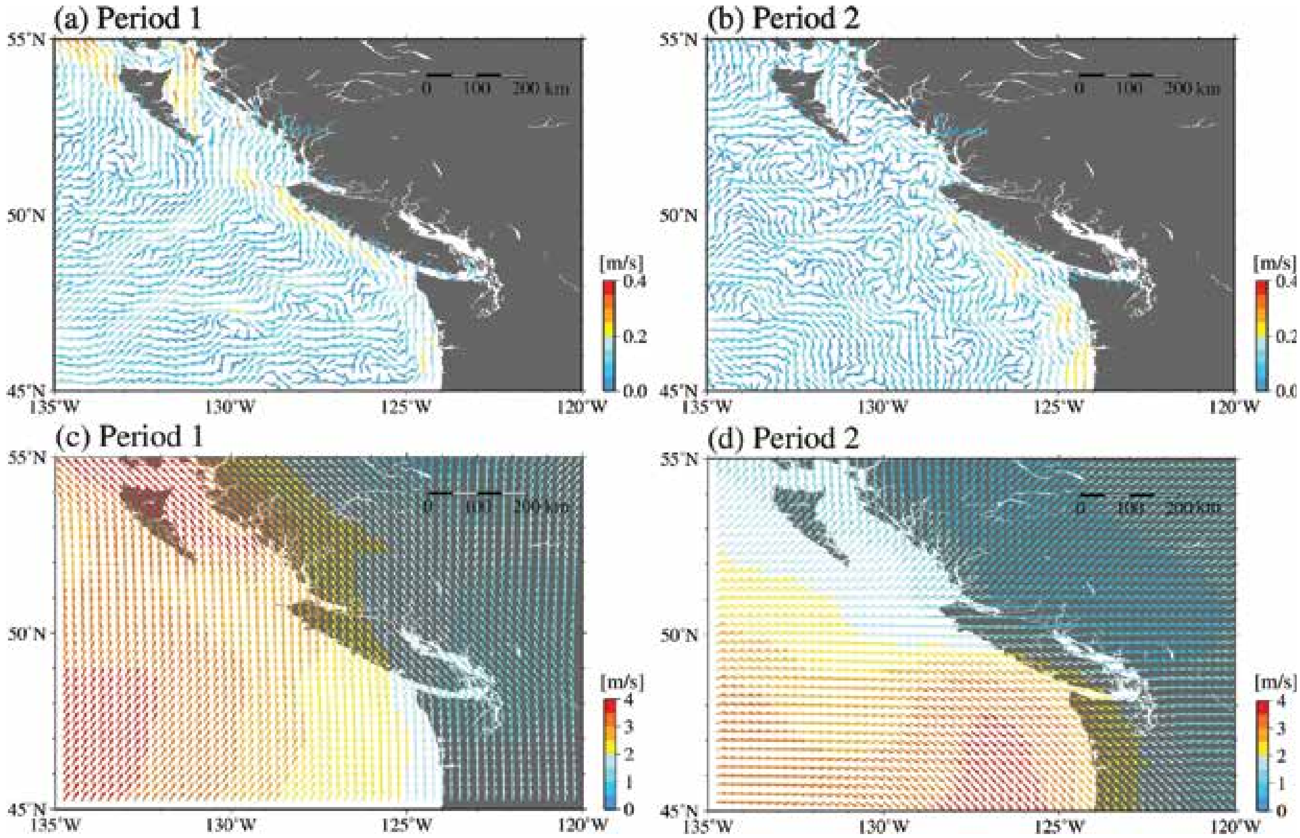


Figure 5-6. Sea surface mean current (a, b) and mean wind (c, d) vector fields during period 1 (fall and winter; left panels) and period 2 (spring and summer; right panels). The color scales of current and wind speeds are shown on the right of each panel.

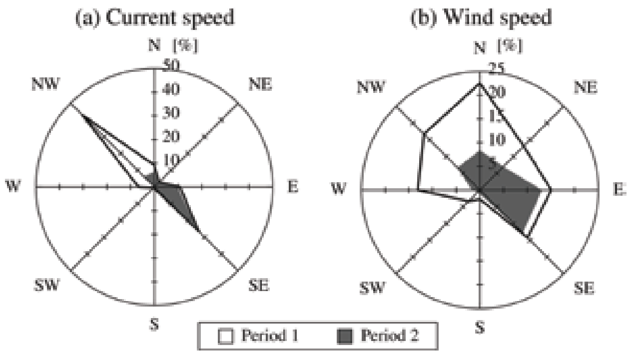


Figure 5-7. Current (a) and wind (b) roses using data averaged over the red broken line in Figure 5-1b after smoothing by the 7-day moving average. The frequency of each direction during 2014 is depicted by a bold solid line. The white area (enclosed by the bold solid line) indicates the frequencies of current/wind during period 1 (period 2).

The current fields averaged over period 1 (Figure 5-6a) show that the strong northwestward coastal boundary current was approximately along the 500-m isobath (see Figure 5-1b) while the relative weak southeastward boundary current occurred in period 2 (Figure 5-6b). This seasonal variability is consistent with Mysak (1983) where an annual cycle of the California Current System was described on the basis of current meter moorings. The wind fields averaged in each period (Figure 5-6c and d) demonstrate that the northwestward winds were relatively strong in the northwestern part of Vancouver Island while the southeastward winds in period 2 were relatively strong in the southeastern part. This was associated with the northwestward and southeastward wind waves (and hence, Stokes drift) enhanced in periods 1 and 2, respectively. The surface currents off Vancouver Island were directed toward the coast during period 1 (Figure 5-6a) while the offshore currents off the southeastern part of the island were directed offshoreward during period 2 (Figure 5-6b). This is consistent with Ekman flow associated with northward (Figure 5-6c) and southward (Figure 5-6d) winds in periods 1 and 2, respectively.

Discussion

Relationship between debris accumulation and current and wind patterns

Almost all beaches on the west coast of Vancouver Island face south and southwest (Figure 5-4a), and thus, the northward and northeastward (i.e., onshoreward) motion of marine debris is favorable for it washing ashore. We next considered the contributions of ocean currents, wind waves (hence, Stokes drift), and sea winds (hence, leeway drift) on the onshoreward debris motion off Vancouver Island. As the result of the annual cycle aforementioned, northwestward currents were predominant in period 1 and southeastward currents in period 2 off Vancouver Island (Figure 5-7a). Thus, these alongshore currents are unlikely to increase marine debris washed ashore on the south- and southwest-facing beaches dominant on Vancouver Island. Nevertheless, relatively large percent cover in the southeast-facing beaches (Figure 5-4b) might result partly from the predominance of northwestward currents in period 1. Of particular importance is the onshore Ekman transport off Vancouver Island in period 1 (Figure 5-6a), which was likely to carry the marine debris drifting in the offshore area toward the coast under the downwelling-favoring northward winds (Figure 5-6c).

It should be noted that northward and northeastward (i.e., onshoreward) winds were intensified in period 1 (Figure 5-7b). The marine debris would be efficiently transported onto the south-facing and southwest-facing beaches (Figure 5-4a) owing to the leeway drift associated with these onshoreward sea winds. The contribution of winds, irrespective of their direction, was likely, especially in period 1 because the frequency distribution of percent cover (Figure 5-4b) seemed approximately (not exactly) to be a "mirror image" of that of the wind directions in period 1 (Figure 5-7b). In addition to the leeway drift, marine debris would be carried by northward and northeastward Stokes drift associated with wind waves forced by onshoreward winds, although additional field surveys such as drifter experiments are required for the contribution of Stokes drift to be conclusive.

The marine debris washed ashore was likely to occur especially in period 1 (fall and winter). This is because the favorable conditions for onshore Ekman flows (Figure 5-6a) and onshoreward winds (hence, leeway and Stokes drift; Figure 5-7b) appear in this season. However, the relative importance among these three causes remains unknown in the present study, unless the time series of debris abundance, winds, and ocean currents are concurrently investigated (see Chapter 4; Kako et al., 2018). The predominance of marine debris in period 1 is consistent with the spatial distribution of percent cover (Figure 5-3). The northward winds in period 1 intensified toward the northwest off Vancouver Island (Figure 5-6c), and thus, eastward Ekman flows, northward leeway drift, and northward Stokes drift were all likely to carry marine debris onto the southwest-facing beaches. In fact, the accumulation of marine debris in the northwest of Vancouver Island was higher than that in the southeast (Figure 5-3). Conversely, the southeastward alongshore currents in period 2 were likely to contribute to the accumulation on west- and northwest-facing beaches although there were very few beaches in this region (Figure 5-4a). Also, onshoreward winds occurring in period 2 (Figure 5-7b) had a role to increase marine debris on the beaches although the frequency was smaller than that of period 1. In the near future, we will investigate the mechanism to accumulate marine debris on various beaches of Vancouver Island using more quantitative methods such as particle tracking models.

The dependence of debris abundance on the ocean currents and sea winds close to the beaches is useful information to determine priority sites for debris monitoring and shoreline cleanup activities. In order to reduce the adverse impacts of marine debris on marine ecosystems and resources, we need to carefully select the sites when these activities are conducted because the effectiveness of these exercises is likely to highly depend on appropriate site choice. It is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difficult to conduct these activities concurrently on multiple beaches because of the limitation of human and financial resources. This study suggests that the current and wind patterns in the offshore region of the study fields can provide us with useful indices of debris abundance.

Applicability of the aerial photography and image processing

It should be noted that quantification of debris abundance based on the aerial photographic survey and our image processing has two limitations. First, the aerial photographs taken on beaches with identifiable land features (e.g., large rocks) should be selected to apply our image processing since the projective transformation was incapable of processing aerial photographs of beaches without immobile objects (e.g., sandy beaches). In fact, in the present study we were unable to compute the percent cover from the eight aerial photographs on Cheewat Beach because of the lack of the appropriate five reference points within the photographs (see validation subsection in Results). Second, only surface debris can be detected by aerial photography. For instance, debris washed into back-beach vegetation and/or covered by other debris cannot be quantified using aerial photographs. Nonetheless, the aerial photographs are capable of approximating the debris abundance because the abundance observed by both the present analyses and in-situ surveys exhibit similar patterns (Table 5-2). However, we have to note that the debris abundance may be underestimated in comparison with the in-situ surveys, especially in the case that marine debris washed ashore for a long time is deeply "stratified" within relatively narrow and/or back-beach vegetation areas. This is especially true on high energy beaches (strong wind and/or wave action), and where vegetation is present immediately upland from the beach. LIDAR technology (Ge et al., 2016) might overcome the above limitation because the laser scanner can measure a volume of objects on a beach by identifying their three-dimensional structure. However, the LIDAR survey has a disadvantage in that the accuracy of the estimate is reduced as the beaches increase in topographic undulation. The volume of marine debris, for instance, is underestimated if a portion of the beach is sunken.

Our aerial photograph image processing has an extra advantage regarding the "re-analysis" of archived aerial photographs of marine debris of the past. The projective transformation method can be applied to archived photographs by setting at least four referencing points within the photographs using the satellite visual images provided by Google Earth. The Alaska Department of Environmental Conservation, for instance, has also conducted aerial photographic surveys to monitor JTMD potentially washed ashore along the south coast of Alaska. The aerial photographs with six debris rankings (Table 5-1) are publicly available[3]. Applying the image processing techniques of the present study to these archived aerial photographs may be used to further investigate the spatio-temporal variability of marine debris, including JTMD, over broad areas. Recently, ortho-imagery surveys (aerial photography taken orthogonally to the ground) were conducted for marine debris on the main Hawaiian Islands (see Chapter 6; Moy et al., 2018). Ortho-imagery has an advantage over the present procedure such that areas covered by marine debris can be directly computed from the photographs without additional georeferencing, while the disadvantage is the high cost, one order of magnitude more expensive than our procedure. Therefore, aerial photographic surveys have an advantage in cheaply and efficiently monitoring marine debris abundance over broad areas even if in-situ surveys on the beaches are prevented because of inaccessibility.

Conclusions

We have developed an image analysis technique to quantify JTMD abundance with high spatial resolution using archived aerial photographs. The aerial photographs were processed by projective transformation and by extraction of debris pixels. In our image analysis technique, the percent cover, a ratio of an area covered by marine debris to the area of the beaches taken by aerial photography, was adopted to indicate debris abundance. The percent cover was validated by comparing with the number of marine debris objects per unit area (surface number density) measured by the shoreline in-situ survey on two beaches of Vancouver Island. The ratio of percent cover of the two beaches was consistent with the ratio of surface number densities. Marine debris tended to have higher accumulation on the northwestern part of Vancouver Island than the southeast. In addition, the horizontal distribution of percent cover was significantly related to offshore Ekman flows and winds (leeway drift and Stokes drift), and the accumulation occurred especially in fall and winter (period 1) when these oceanic and atmospheric conditions become favorable for marine debris to wash ashore. We used Google Earth satellite images to provide the reference points for the projective transformation. Hence, this image analysis procedure was capable of processing archived aerial photographs even if the physical reference points were not predetermined. Therefore, in-depth examination using archived aerial photographs can provide additional information about the places and time periods with higher debris accumulation and arrival of JTMD which has gradually increased since 2011.

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[3] http://www.arcgis.com/home/webmap/viewer.html?useExisting=1&layers=555996dd72e84b6c9fa2952692fe85d2

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THEME II – Arrival of Debris

Chapter 6: Surveillance of debris in the main Hawaiian Islands[1]

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Abstract

Aerial surveys of the eight main Hawaiian Islands (MHI; Hawaii, Maui, Oahu, Molokai, Kauai, Lanai, Niihau, Kahoolawe) were conducted and the resulting imagery was analyzed to identify and quantify marine debris on Hawaiian coastlines. The analysis concluded that about 12% of coastlines are areas of high marine debris accumulation, concentrated primarily on windward (north- and east-facing) shores. The debris was evenly distributed throughout the MHI with the exception of Niihau, the northernmost and privately owned island, which had the highest concentration of debris (38% statewide). All other islands had less than 14% each, with Oahu being the least dense at just 5% statewide.

In total, the study counted over 20,000 individual items of macro-debris (> 0.05 m^2). Plastics were overwhelmingly the dominant debris type by category, accounting for 80% of total debris. Vessels, metal, cloth, tires, processed wood, and unknown debris types made up the remaining 20% combined. This study provided a baseline of marine debris densities at a moment in time, and we worked with federal, state, and local agencies to prioritize areas of highest need for debris removals and monitoring. In addition, the analysis identified 52 vessels from the imagery that were difficult to definitively classify as abandoned and derelict vessels (ADVs). The study arranged for all 52 vessels to be further scrutinized through in situ evaluations and determined that only 30 vessels were in fact ADVs. Ten were identified as potential Japanese Tsunami Marine Debris (JTMD), four of which were soon after officially confirmed as JTMD by the Japanese Consulate.

The final phase of refining the aerial survey analysis was the investigation of marine debris cleanup events that occurred prior to the flyover dates for each island. The study received removal data from over 20 federal, state, city, county, and private groups totaling more than 2,000 cleanups. This effort represented at least 70 metric tons of debris removed and well over 30,000 man-hours. The time elapsed between flights and cleanup dates was used to evaluate any potential impact of debris removal on the apparent debris accumulations for a segment, and this spatial information was then made publicly available online. Most importantly, the overall goal of the study was to prepare a public resource to share its findings. These data are available in an online ArcGIS Story Map at http://arcg.is/29tjSqk and the imagery is also available publicly through the Hawaii State Office of Planning.

Introduction

In order to evaluate the potential ecological consequence of debris from the Great Japan Tsunami of 2011, it is important to characterize the debris itself. Understanding the type, size, and location of debris accumulating on Hawaiian coastlines is crucial in developing plans to streamline the removal process and mitigate any negative impacts this debris may have on the islands and their inhabitants. Given the vast extent and remoteness of coastlines in the Hawaiian Islands, large-scale surveillance efforts are necessary to identify and describe these accumulations. Capture and analysis of high-resolution aerial imagery allows for rapid qualitative and quantitative assessments at this scale, providing data that can be used to evaluate marine debris accumulation patterns in Hawaii, and plan further management actions.

The objective of our contribution to the Assessing the Debris-Related Impact From the Tsunami (ADRIFT) project was to document and describe marine debris on coastlines of the MHI through high-resolution aerial imagery paired with ArcGIS mapping software and to develop and demonstrate this method as a feasible option for large-scale macro-debris surveys. Additionally, we aimed to distribute our findings through peer-reviewed journal publication (Moy et al., 2018), presentations, conferences, and online resources.

Methods

The study was divided into a series of stages: (1) collect and process the high-resolution aerial imagery of the MHI coastlines to create ArcGIS image files, (2) analyze this imagery using ArcGIS software to identify, quantify, and categorize each distinct point of debris and use the collected data to generate maps and figures of debris composition, density, and distribution for each island as

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[1] A reduced version of this chapter first appeared in PICES Press Vol. 25, No. 1, 2017. A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 52-59.


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well as statewide, and (3) refine the results through in situ ground-truthing of suspected ADVs and analysis of prior beach cleanups.

Aerial imagery collection and processing

Resource Mapping Hawaii (RMH) was contracted by PICES and Department of Land and Natural Resources (DLNR) to conduct aerial surveys from a Cessna 206 between August and November 2015. Using an array of three digital single-lens reflex (DSLR) cameras, multiple photos were captured every 0.7 seconds while flying at an average ground speed of 85 knots. The cameras were mounted on a three-axis stabilizer gimbal to ensure that photos were taken within 4 degrees of crab, roll and pitch angles. The mapping system also included differential GPS to collect latitude, longitude and altitude data. The surveys had a target altitude of 2,000 feet (~600 m) above ground level to achieve a ground resolution of 2 cm per pixel and a swath width between 200–300 m. Areas where flight restrictions apply, such as military bases and airports, were excluded from the imagery collection process. Using custom photogrammetry software, the aerial photos were mosaicked and ortho-rectified to an accuracy of 5 m root mean square (RMS), then divided into GeoTIFF raster tiles for use in ArcGIS.

Imagery analysis for debris composition, density, and distribution

Marine debris type was classified into seven categories (Table 6-1) prior to GIS analysis. While there were limitations on the ability to determine debris types at this scale, categorization of identifiable debris was useful to understand trends in debris accumulation (Figure 6-1). If a piece of debris was made up of more than one type of material, the main material was listed and the additional materials were included as a comment. The macro-debris was also categorized into four size classes: very small (< 0.5 m^2), small (0.5–1.0 m^2), medium (1.0–2.0 m^2), or large (> 2.0 m^2). Size was measured as the approximate area of the object in meters squared, estimated using the measurement tool within ArcGIS.

Line shapefiles divided each MHI's coastline into 1.6-km segments, and tile outlines of polygon shapefiles were created for each of the imagery raster tiles, thus matching the aerial imagery files to the segment of coastline they depict. Each segment was systematically surveyed and every point of debris recorded with its latitude, longitude, category, size, observer, and any relevant comments (Figure 6-2).

Segments were further categorized by debris density; any segment with 100 debris items or more was considered a "hotspot" of debris accumulation. During the statewide analysis process, all segments were regrouped into 8-km lengths to improve the visual usefulness of the statewide accumulation map at the required scale.

Refining the data: In situ ground-truthing ADVs and beach cleanup analysis

The study recognized two shortcomings to the aerial imagery analysis: (1) the resolution was not fine enough to determine whether vessels were in use, abandoned, or truly marine debris, and (2) the analysis did not take into account the possibility that a beach cleanup group may have removed debris immediately prior to the aerial surveys, potentially altering the segment's classification as a marine debris hotspot. In the third phase of the study, we attempted to address these deficiencies.

All debris items detected and categorized as vessel were inspected to verify their respective status as marine debris. Each vessel's position relative to the highwater mark, location, condition, and description was measured in situ. Additionally, the study used historical imagery from Google Earth (2016) to evaluate the likelihood of a vessel being JTMD; if a vessel was present in the imagery before 2012, it was not JTMD. Any suspected JTMD was evaluated for characteristics consistent with confirmed JTMD ADVs such as color, shape, size, and the presence of Japanese letters or registrations (Figure 6-3).

For beach cleanups, we contacted over fifty community members, federal, state, and local organizations, and received more than 2,000 reports of marine debris removals. Those reports were catalogued by date, location, participants, duration, distance covered, and the debris removed was reported in various combinations of item counts, total weight removed, or man-hours. The locations were nearly all reported by common name of the beach or area targeted, and the study approximated the coordinates. Events that only addressed litter or did not occur on coastlines were discarded.

Results

Data for each of the eight islands[2] were analyzed. Marine debris was heavily concentrated on the island of Niihau, which had 38% of the total debris identified across all of the MHI. Other main islands contained less than14% each of the total debris, with Oahu being the least dense, with only 5% of the total debris. Debris density was not reflective of coastline length or number of segments (Figure 6-4). On all MHI, marine debris was primarily concentrated on north- and east-facing shores, with west-facing shores accumulating the least amount of debris (Figure 6-5).

The imagery analysis identified a total of 20,658 pieces of marine debris. Composition of debris varied between islands, but the most common type of debris on all MHI was plastic (not including buoys, floats, net, and line), which made up 47% of the overall composition of debris identified and at least 37% on any individual island. Buoys

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[2] DLNR report, http://dlnr.hawaii.gov/dar/reports/

Table 6-1. Seven categories of marine debris materials observed in the aerial imagery.

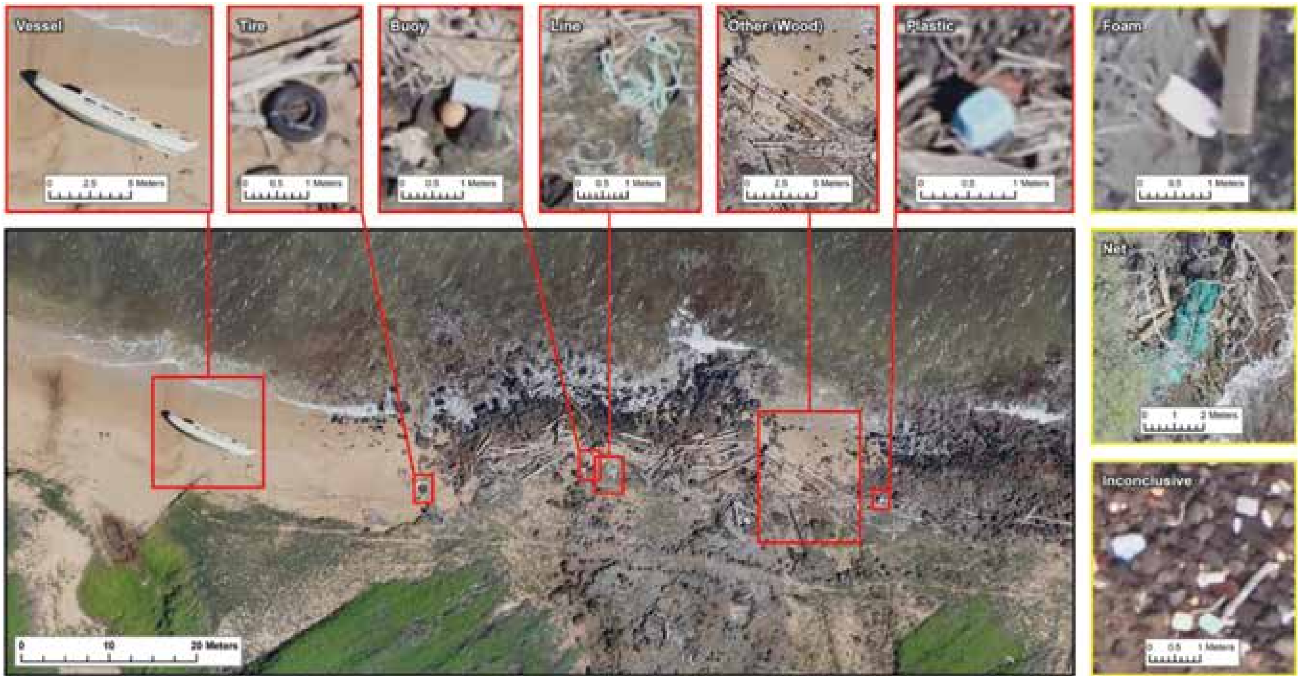
Material	Description
Plastic	Any items made from plastics (with the exception of DFG, buoys, and floats) as well as plastic fragments; usually identified by bright colors and/or sharp edges
Buoys and floats	Any float used for mooring, as a buffer for boats, marking a channel, or fishing; can be plastic, glass, rubber, foam or metal
Derelict Fishing Gear (DFG)	Includes all woven netting and any type of line such as rope, fishing line, twine, etc.
Tires	Full tires and tire treads
Foam	Includes flotation, insulation and packaging material
Other	Items consisting of processed wood, metal or cloth, as well as vessels and vessel fragments that appear abandoned or derelict
Inconclusive	Items that were identified as marine debris but could not be confidently classified into a material category

and floats and derelict fishing gear were the next largest categories when comparing total debris counts, at 22% and 11%, respectively. Between islands, however, the amount of debris in these categories varied from 8% to 35% (average of 19%) for buoys and floats, and from 5% to 21% (average 11%) for derelict fishing gear. As the vast majority of buoys, floats, foam and derelict fishing gear are plastic, the total average plastic composition of debris on any one island was around 80%. Tires and foam each made up less than 10% of the debris on any island, and 5% and 3% across all islands, respectively. "Other" category items (items identified as processed wood, metal, cloth, or vessels) contributed 6% to the overall debris count, and inconclusive items contributed 7%, with varying degrees of density across islands.

The size class distribution of identified debris was far more uniform across all MHI. The "very small" category (< 0.5 m^2) made up 86% of the total debris found on all the MHI, and contributed from 84% to 89% on any one island. The remaining categories each made up less than 10% on any island, with the total contribution statewide from the small category (0.5 m^2–1 m^2) being 6% and the total contribution from the remaining size classes (1 m^2–2 m^2 and > 2 m^2) being 4% each. Items much smaller than 0.5 m^2 were increasingly difficult to distinguish in the aerial imagery.

Larger items such as vessels proved easier to identify and measure, but still posed challenges to the analysis. Of the original 52 vessels detected in the aerial imagery analysis,

Figure 6-1 (below) Sample swath of coastline and the variety of debris identifiable in the high-resolution imagery. Items on the right (yellow outline) were found elsewhere and are included to demonstrate examples of the other debris types (from Moy et al., 2018).



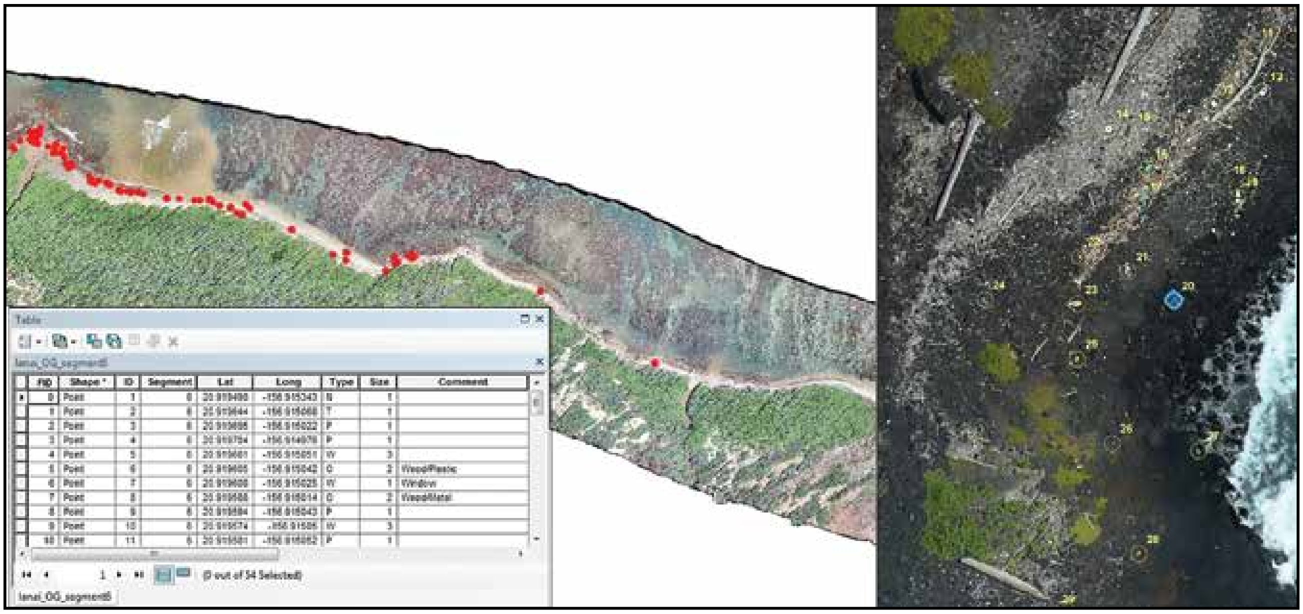


Figure 6-2. A swath of Kauai coastline in ArcGIS and the data table of the identified debris (red dots; left), with a zoomed screenshot of marine debris identified by numbers on Kamilo Point, Hawaii Island (right).

Figure 6-3. Three JTMD vessels detected in the aerial imagery (left) and their corresponding in situ photo (right).

only 30 were determined to be ADVs. Of those, the study was unable to locate six based on the coordinates observed in the aerial imagery. These vessels were presumed lost and in five cases, broken pieces of wood, an engine, a Japanese fuel pump, fragments of registration numbers, and other evidence were observed, seeming to indicate that the vessels were washed out and broken up after being captured in the imagery. All six of the lost vessels shared characteristics with other JTMD ADVs, and the Japanese Consulate later confirmed three as JTMD. In total, four suspected JTMD ADVs were submitted to the Consulate, National Oceanic and Atmospheric Administration (NOAA), and DLNR Division of Boating and Ocean Recreation for confirmation.

Once the imagery analysis concluded, beach cleanup data were compiled to evaluate the potential influence of removals on shoreline density ratings. A total of 2,134 individual cleanup events were reported to the project by 21 separate organizations at the federal, state, local, and private level. Only 376 of those were conducted within 365 days of a flyover date for the corresponding island, and occurred on 68 out of the 1,223 segments, or approximately 5% of the full coastline of the MHI. Within two weeks of flights, there were only 16 cleanups that took place on 10 different segments. Four of those cleanups may have caused the analysis to underestimate the appropriate rating for their corresponding segment, but these amounts of debris removed do not alter the overall distribution of debris between islands by more than 1%. Only one cleanup was conducted on the same day as a flyover on Kauai and involved a few derelict fishing gear removals, but the small numbers removed would not have altered the segment rating even if it occurred after the imagery was taken (Figure 6-6).

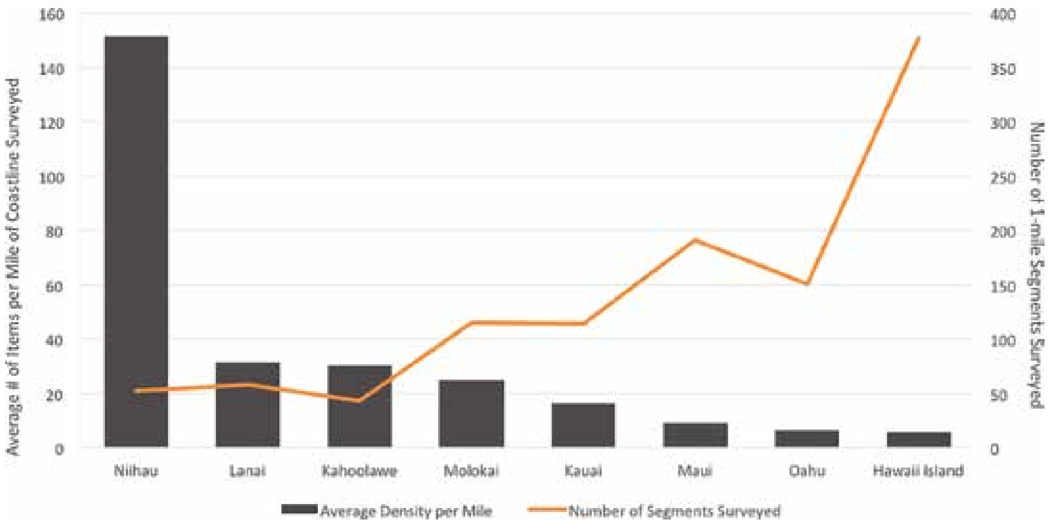


Figure 6-4. Average number of debris items found per 1-mile (1.6-km) segment of coastline for the main Hawaiian Islands (MHI) in relation to total coastline length, in miles.

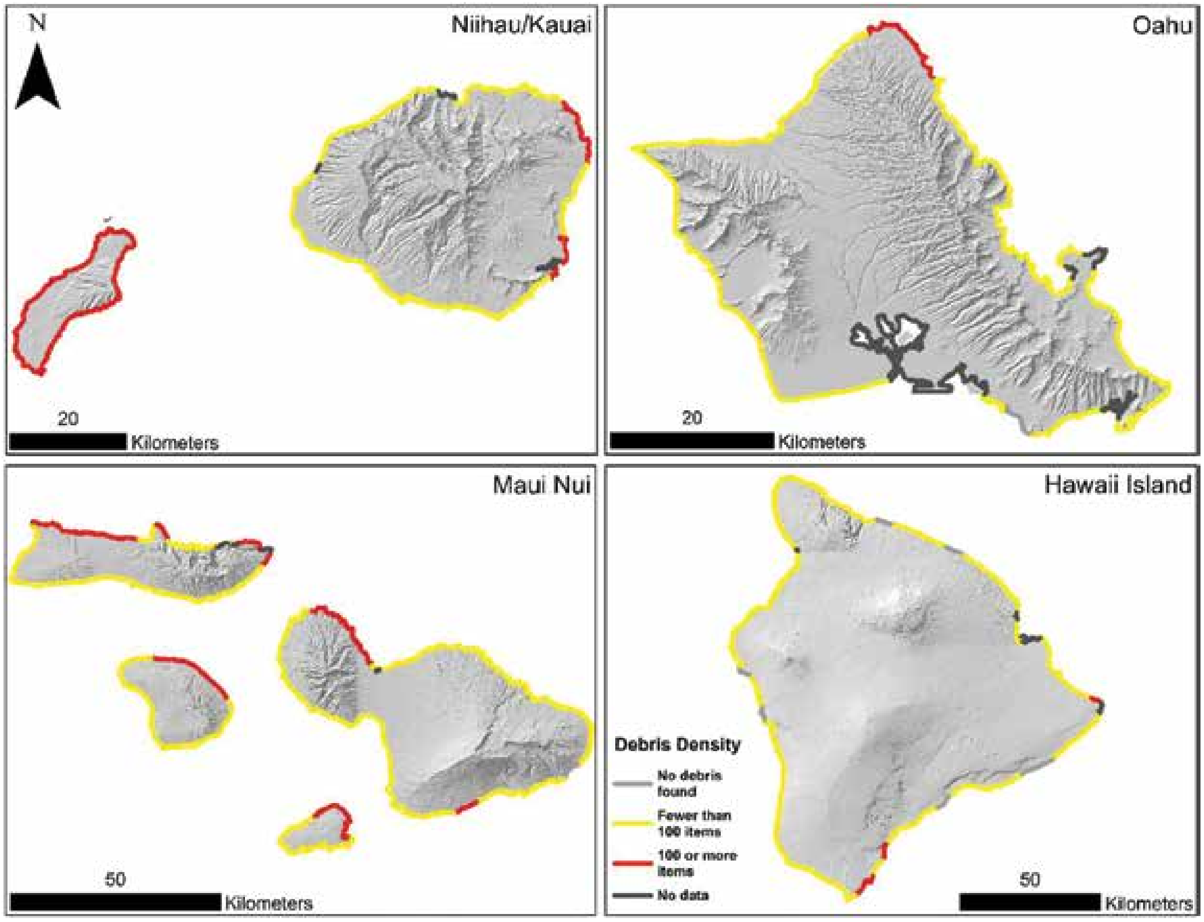


Figure 6-5. Density and distribution of debris on the MHI showing marine debris "hotspots," segments with 100 or more items. Segments were divided into 8-km lengths to improve visual interpretability.

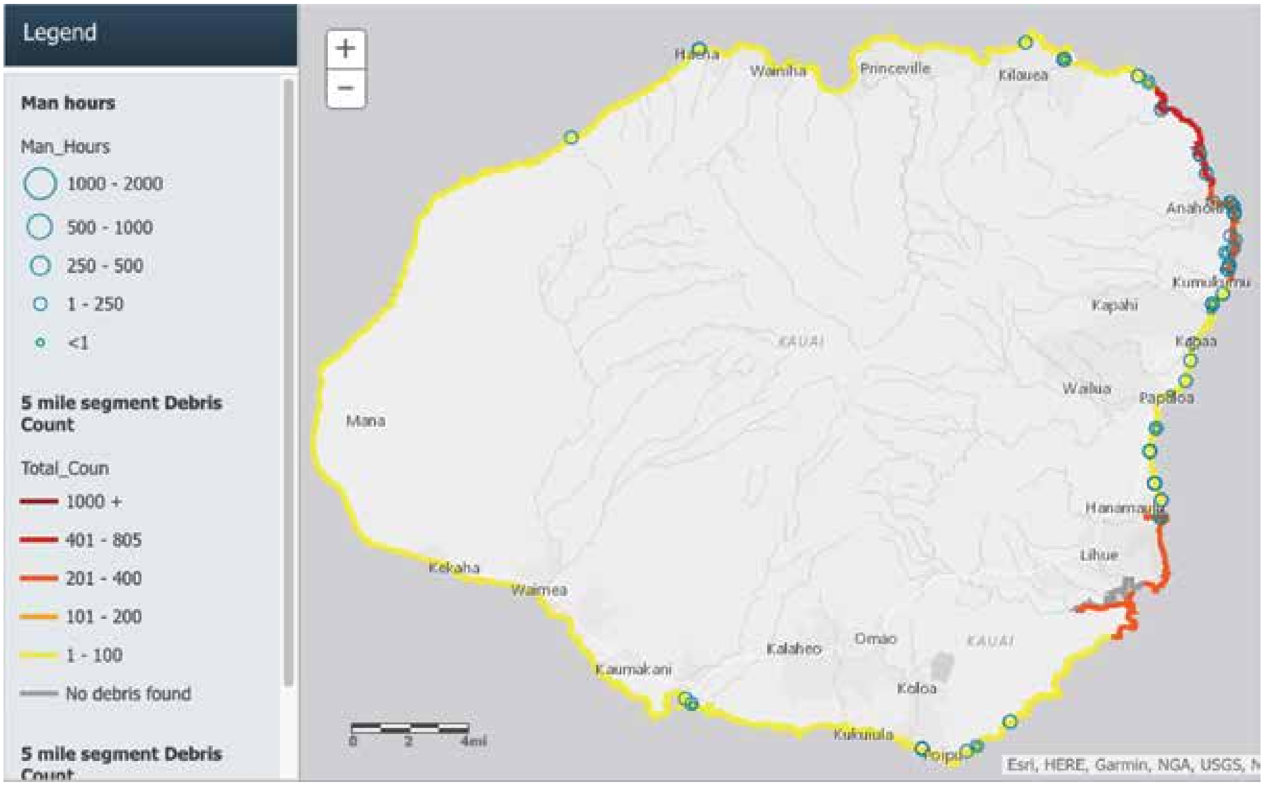


Figure 6-6. Sample screenshot of Kauai showings how man-hours were mapped over segment ratings.

Discussion

Imagery capture methodology

Marine debris is detected by a variety of technologies beyond aerial surveys with different results. NOAA (2015) compared the more common methods for detecting JTMD and prioritized high-resolution and wide-range coverage due to the diversity of debris types and spread of debris fields at sea. In this evaluation, the NOAA report concluded that satellite sensors are at the boundary of their ability to detect small debris and that the currently available unmanned aerial system (UAS) platforms were still inadequate and experimental. UAS can offer higher resolution but do not have the required range to replace aerial surveys. While both of these technologies are being further developed and improved, the most effective method available for both land-based and at-sea detection of marine debris is the aerial platform.

Previous attempts to locate and characterize debris in the MHI through aerial surveys were done at oblique angles and relied on in-flight observations rather than post-flight analysis (PIFSC, 2010). Similarly, high-resolution imagery techniques have been employed elsewhere using oblique imagery from a fixed winged aircraft (Kataoka et al., 2018), balloon (Nakahima et al., 2011), and webcam (Kako et al., 2010; Kataoka et al., 2012). However, inconsistent altitude, angles, and positions at the moment of each photo's capture presented challenges in precision and accuracy of the imagery. Overall, the combination of 2 cm resolution and ortho-rectified mosaicked imagery allowed our analysts to pan seamlessly through the coastlines of each island. When the team encountered items that were difficult to identify, it was easy to revisit the imagery with other analysts or even provide latitude and longitude coordinates for in situ ground-truthing. The imagery is useful beyond marine debris and can be used for a variety of other purposes, including wildlife observations, sediment runoff, historic and cultural landmarks, and shoreline erosion.

The analysis

The distribution of debris within the MHI strongly indicated the prevalence of debris on the windward side, as 76% ± 7.1% of debris was found on north- and east-facing shores. This was likely due to a combination of oceanic drivers, particularly a northwesterly current running alongside the east of the island chain and the prevailing trade winds from the northeast that drive debris from the Pacific Garbage Patch (PIFSC, 2010; Blickley et al., 2016). These factors may also explain why Niihau, the northernmost main Hawaiian Island, had 38% of all debris in the state and the rest of the MHI had less than 14% each. It is important to evaluate the relative abundance of debris within the eight MHI to assist regulatory agencies like the DLNR and community cleanup organizations with prioritizing debris removal efforts, resources, and monitoring to improve the overall understanding of marine debris' impact in the state.

The study was limited in its ability to detect items much smaller than a detergent bottle on the shoreline. Though the imagery was high-resolution, categorizing debris became increasingly difficult with smaller items. Despite the difficulty in detecting small items, very small (< 0.5 m^2) items were the majority of all debris found. Items in this smallest size class are predominantly plastic (Gregory and Ryan, 1997; Morét-Ferguson et al., 2010; Martins and Sobral, 2011) and given the study's inability to detect the smallest items on the beach, the proportion of plastics in the debris makeup is likely severely underestimated. The dominance of plastic on the beach is consistent with a review by Gregory and Ryan (1997) that found plastics accounted for 60–80% of all debris in a number of studies. The global use of plastics has increased over the past 45 years and its proliferation continues to exacerbate the problem of marine debris, and more recently, microplastics in our environment (Derraik, 2002; Vegter et al., 2014; Barboza, 2015; Gall and Thompson, 2015). While the current survey was unable to address the question of microplastics, the prolific abundance of plastic within the overall debris makeup suggests a more insidious problem that modern sensor technologies cannot adequately measure.

Refining the results

Following the analysis, the in situ ground-truth observations for vessels demonstrated the shortcomings of the imagery to identify whether a vessel was an ADV or in use. However, the method proved very effective in detecting and locating vessels. Since the first JTMD vessel was reported in the MHI in 2012, there have been four to ten JTMD ADVs reported each year (DLNR, 2016, pers. comm.). In 2015, ten vessels were reported to DLNR. The aerial surveys increased detection by nearly 2-fold, identifying eight unreported potential JTMD vessels. These ADVs were nearly all in isolated and relatively inaccessible coastlines where marine debris goes unreported, further demonstrating the advantage of the aerial surveys. Additionally, six of those eight vessels were lost within 6 months of initially being detected on shore. Finding and removing ADVs is extremely time sensitive to reduce the threat of a vessel returning to sea and inflicting further harm on the marine environment.

The results of the beach cleanup analysis demonstrate that the removals from 2015 had little to no discernable effect on the statewide hotspot assessment. Beaches where debris cleanups occurred regularly were still hotspots of marine debris accumulation. However, these hotspots were rated using a measure of relativity – segments with more than 100 debris items. Niihau had a segment with over 1,000 pieces of debris. Statewide cleanups may have an impact on the unequal distribution of debris between the eight MHI, particularly between Niihau (38%) and Oahu (5%), but further research on the rate of deposition and the oceanic processes affecting the individual islands is needed.

Challenges

Initially, capturing the imagery proved to be a challenge for the study's partner, Resource Mapping Hawaii. All flights had to be scheduled in as short a time frame as possible to reduce the influence of temporal variations on debris accumulations. There were restricted airspaces that had to be omitted from the process, and several areas of coastline presented a hazardous challenge as the Cessna aircraft attempted to maintain the necessary altitude without flying too closely to some of Hawaii's more dramatic coastlines. About 10% of the coastlines of the MHI were left out of the analysis due to these challenges.

During the analysis, the team made an unexpected improvement in processing speed. The first few weeks started out slowly as the analysts familiarized themselves with the protocols and the software, but after a month their efficiency increased dramatically. The imagery mosaicking process eventually became the bottleneck of progress. The analysts revisited the segments they initially processed to perform quality control and also to re-evaluate some of the unidentified debris, having become more familiar with the different types of marine debris in the imagery.

There were limitations in the study with the chosen method of a snapshot accumulation study. Seasonal variation and change over time could not be measured with a single set of flyovers, but it did provide a baseline for future accumulation studies. The study also did not plan for the possibility of a cleanup organization clearing all the debris from a segment the day before the flyovers. In the third phase of the study, we were able to verify there were no cleanups immediately prior to the surveys. In future aerial survey studies, local cleanup groups should be notified and asked to refrain from cleaning the coastline until after the flights are completed. Starting in 2017, Hawaii's cleanup organizations entered into a new data-sharing endeavor to increase transparency and coordination to cleanup efforts throughout the MHI. The results of this collaboration were published in an ArcGIS Story Map at https://arcg.is/0aDSTi.

The study was successful in creating a baseline of marine debris in the MHI and was the first comprehensive debris evaluation in the state. Employing a unique methodology, the study provided strong evidence of the accumulation patterns and densities throughout the islands and also identified suspect JTMD items of major concern throughout the Pacific. This first endeavor to collate cleanup data from all organizations throughout the state also initiated a statewide data-sharing movement towards applying the spatial mapping and meta-data analysis techniques from this study to all cleanups in the MHI since 2004. The ADRIFT project inspired a cooperative shift in the marine debris network of Hawaii to better document and share cleanups under the Hawaii Marine Debris Action Plan (NOAA Marine Debris Program, 2016) and the newly formed Hawaii Environmental Cleanup Coalition of 2017, and both its spatial mapping method and aerial survey method are priorities for the state to continue using in the future.

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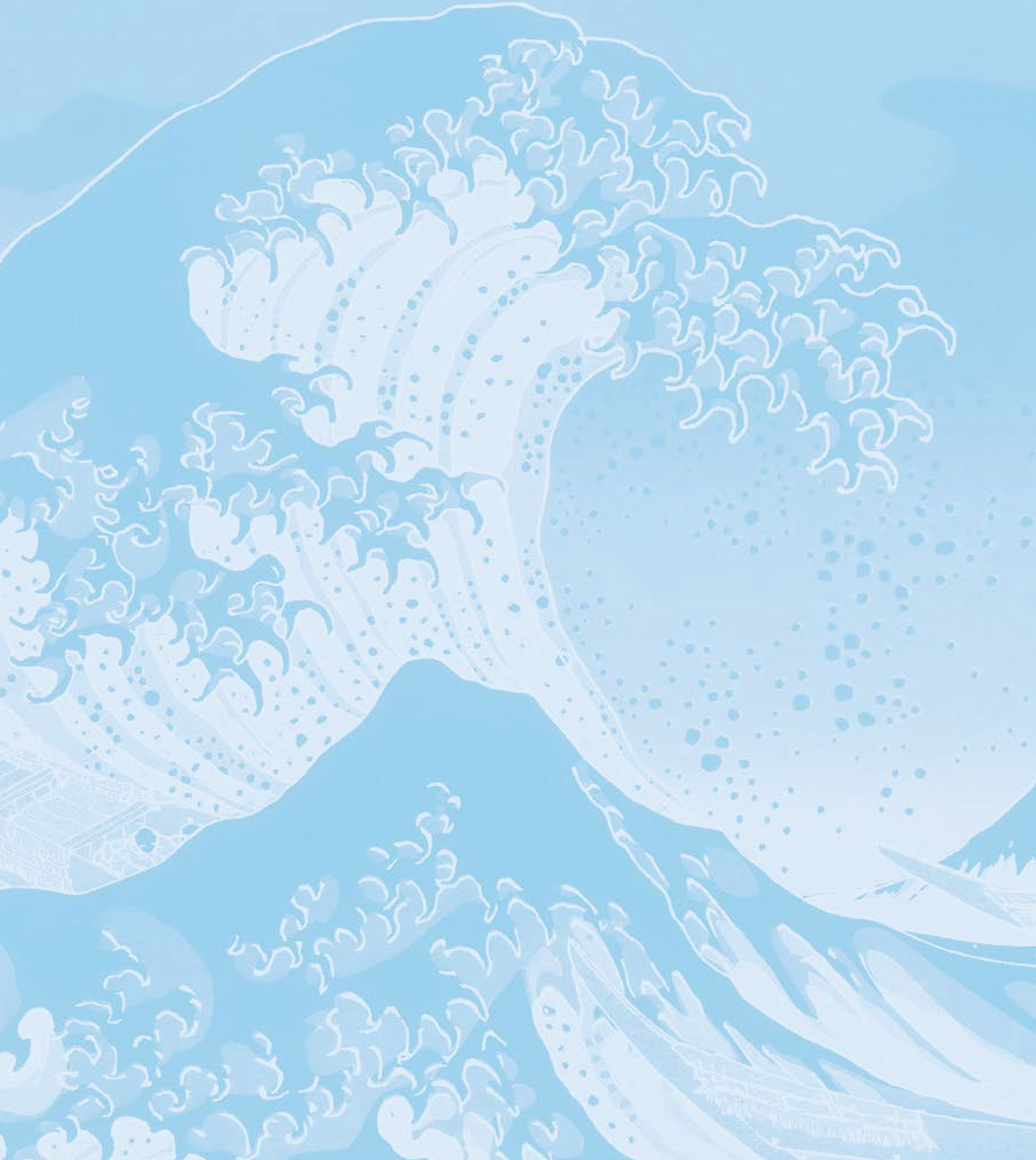

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Chapter 7: Characterization of the invertebrate, protist, and fish biodiversity arriving with Japanese Tsunami Marine Debris in North America and the Hawaiian Islands[1]

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Abstract

Six hundred and thirty-four objects related to the Great Japan Tsunami of 2011 that arrived in North America and the Hawaiian archipelago were studied for the diversity of attached marine life. Objects included vessels, totes, buoys, docks, post-and-beam wood, and many other items associated with Tohoku coastal communities on Japan's Honshu Island. Object arrival over time demonstrated a relatively consistent pattern of spring pulse landings. Nearly 300 species of marine invertebrates, protists, and fish have been detected on the debris field since 2012. Remarkably, at least seven new species of marine life have been detected on Japanese Tsunami Marine Debris (JTMD). Invertebrate diversity was dominated by six groups: mollusks (bivalves, gastropods, and chitons), polychaetes (marine worms), cnidarians (hydroids and sea anemones), bryozoans (moss animals), crustaceans, and sponges. Cumulative species richness mirrored the annual debris arrivals in spring, resulting in staircase-like pulses. Eight invertebrate species occurred on 35 or more objects. More than 50% of all objects with living species transported the Mediterranean mussel *Mytilus galloprovincialis*, a 20th century invasion into Japanese waters. The bryozoan *Scruparia ambigua* was also very common and occurred on one-third of all objects. Adding to the expectation that a subset of the marine fauna from the Tohoku coast would be transported on JTMD, a guild of nearly 40 species was acquired by the debris from south of the Tohoku coast during ocean rafting. These species appeared to have largely settled as larvae while the debris drifted into more southern waters. The number of southern species appearing on JTMD more than doubled between 2012 (3 species), 2013 (11 species), and 2014 and later (27 species), suggesting that the debris continued to take a wider and longer circuitous path through lower latitudes over time.

Introduction

The goal of the biodiversity portion of the PICES ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project was to assess the overall diversity of the invertebrate, protist, and fish fauna associated with the debris field generated by the Great East Japan Earthquake and Tsunami of March 11, 2011, which subsequently rafted, over the ensuing years, to the Hawaiian Islands and to North America. Our objectives were: (1) to obtain the widest variety of biological samples over time and space as feasible and practicable, to process and sort these to the lowest possible taxonomic level to permit identification either in the laboratory or by sending specimens to specialized taxonomists and for genetic analyses, and (2) to analyze the data for diversity patterns over time and space. A corollary effort was focused on providing bivalve samples (particularly the mussel *Mytilus galloprovincialis*) for parasite analyses and fresh tissue samples (see Chapter 10).

Methods

Sample acquisition and processing

We established an extensive network of local, state, provincial, and federal officials, private citizens, and environmental groups in Alaska, British Columbia, Washington, Oregon, California, and Hawaii. Protocols for retrieving, collecting, and acquiring biological samples were developed in cooperation with colleagues on the Pacific coast, and with colleagues in the State of Hawaii, in terms of real-time alerts and communication, notification, quality collection acquisition, and photo-documentation. As a result, many hundreds of preserved samples from JTMD, or items suspected to be JTMD, were received at our laboratory at the Maritime Studies Program of Williams College and Mystic Seaport in Mystic, Connecticut, USA. When appropriate, selected samples were then prepared and forwarded to the Moss

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[1] A version of this chapter was published in a special issue of *Aquatic Invasions* (2018), 13: 1-186.


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Landing Marine Laboratories (MLML, Geller Laboratory) and the Smithsonian Environmental Research Center (SERC, Ruiz Laboratory).

Each sampled object was assigned a unique JTMD-BF-# (Appendix 7-1), beginning with JTMD-BF-1. A continuous registry was then built over the years, with copies being regularly distributed to project participants. All JTMD objects studied in the North Pacific Ocean for Japanese biofouling received, to our knowledge, a BF-#; no other databases were kept independently registering or tracking JTMD items specifically for biodiversity assessment. In order to facilitate authoritative identification of species, 80 taxonomists from 14 countries (Australia, Brazil, Canada, China, Chinese Taipei, England, Germany, Japan, New Zealand, Norway, Russia, Singapore, South Korea, and USA) were engaged (Appendix 7-2).

A very wide array of methods accompanied the detection, assessment, and sampling of potential JTMD objects washed ashore. Those involved in sampling ranged from professional scientists to beach rangers and members of the public. As a result, the nature and extent of samples varied widely over the years. Of the 634 items analyzed, we judged 110 to have been sampled in such a way as likely to have captured the majority of the diversity of species on those objects; these items are referred to as higher resolution (JTMD-HR) objects (Appendix 7-1, asterisked items). Criteria included evidence as to how long the object had been ashore prior to sampling, knowledge of those sampling an item (for example, if persons were sufficiently knowledgeable to recognize bryozoans, hydroids, and similar small or inconspicuous taxa), detailed testimony of the samplers, field photo-documentation, and the volume and quality of sample received. The biodiversity on these 110 objects was then subjected to fine-grained analyses. The remaining 500-some objects, many of which were sufficiently sampled to capture common, larger, and more conspicuous species, such as the mussel *Mytilus galloprovincialis* and the large rose barnacle *Megabalanus rosa*, were examined for broader diversity patterns, as well as to address specific questions on selected species mortality. Further details of materials and methods are provided in Carlton et al. (2017).


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Weather Channel

Identification of objects as JTMD

A variety of methods have been employed to distinguish JTMD – that is, objects specifically lost from the Japanese coast on March 11, 2011 – from ocean marine debris in general. Highest confidence in designating items as JTMD was achieved through a combination of evidence as follows:

1. **Formal object identification:** Registration numbers or other numeric identification present on an object, the data of which could then be provided to the Japanese Consulate or owner for confirmation.
2. **Known Japanese manufactory:** Unique Japanese manufactory, including buoys, and post-and-beam lumber from Japanese homes and businesses, combined with the absence of prior history of landings of these objects in North America and Hawaii.
3. **Bioforensics:** Objects bearing a biological "fingerprint" of the northeast coast of the island of Honshu, particularly of the fauna of the Tohoku region (with, as noted below, the addition of more warmer-water southern species acquired during ocean rafting). Thus, items bore a non-random diversity typical of the shores of the Aomori, Iwate, Miyagi, and Fukushima Prefectures. If large numbers of non-tsunami objects were arriving, they would be predicted to have species aboard from a wide range of source regions of the Western Pacific Ocean.
4. **Pulse event timing:** Objects arriving in the predicted "tsunami debris pulse window," commencing in steady and increasing numbers from 2012 onward, and characterized by a subsequent decline in item arrivals as the debris field entered its fourth, fifth, and sixth years. If debris items were arriving independently and gradually at a background rate from the Western Pacific, a steady attrition would not be predicted. In turn, prior to 2012, there were no records published in the scientific, historical, or management-policy literature – though marine biology records have been kept on the Pacific coast of North America and in the Hawaiian Islands since the 1850s – of any object landing in the Central or Eastern Pacific with diverse communities of living species from the Western Pacific Ocean. In striking contrast, a consistent novel rhythm since 2012 was observed of objects arriving in North America and Hawaii, including many vessels of the exact type and construction known to be lost from Aomori, Iwate, Miyagi, or Fukushima Prefectures, and consistent with modeled debris arrival timing.
5. **Origin:** 100% of all objects – vessels or otherwise – intercepted in Hawaii or North America since 2012, that thought to be from Japan and have been traced to their exact origins, are solely from Aomori, Iwate, Miyagi, or Fukushima Prefectures. In turn, no losses of numerous vessels (or many other items in large debris fields) have been reported from Japan, other than those due to the earthquake and tsunami, since March 2011.


Nancy Treneman

Parasites and pathogens in JTMD mussels

Mussels (*Mytilus* spp.) were collected from JTMD objects on arrival to the coasts of California, Hawaii, Oregon, and Washington, and these were used to test for the presence of associated parasites and pathogens. Mussels were selected for this analysis because they were frequently present on JTMD objects and are known to host a diverse range of parasites, pathogens, and commensals (hereafter parasites) worldwide, including the hydroid *Eutima* that was detected early on in JTMD mussels (Calder et al., 2014).

A total of 1,158 mussels from JTMD objects have been sampled and tested for the presence of parasites, combining previous work funded by the National Science Foundation with the ADRIFT project. All mussels were visually measured for size and screened for the presence of three conspicuous metazoan parasites using a dissecting microscope: the hydroid *Eutima* sp., copepod *Mytilicola* sp., and pea crab *Pinnotheres* sp. In addition, tissue samples from mussels were collected for two different types of molecular genetic analyses. First, mussel tissue samples were obtained and sent to MLML for genetic identification. Second, tissue samples were obtained and processed for detection of three protistan parasites (haplosporidians, *Marteilia refringens,* and *Perkinsus* spp.) using molecular techniques. For the latter analysis, mussels collected from four JTMD objects (JTMD-BF1, BF6, BF8 and BF23) were used because these objects each had 30 or more bivalves, increasing the likelihood that parasites could be present and detected. In total, we screened 264 mussels using molecular genetic techniques for these parasite taxa. For each molecular assay, we combined three target host tissues (gill, mantle, and digestive gland), which are known locations for the target parasites.

Following an overnight digestion with proteinase K, we extracted genomic DNA from all three tissues sampled, which were pooled into a single extraction, using a Qiagen Biosprint Kit (Qiagen, Valencia, California) following the manufacturer's protocols for animal tissues. All extractions completed within the same day included a blank extraction which served as a negative extraction control for Polymerase Chain Reaction (PCR). Aliquots of the extracted DNAs (50 µL), which were made to avoid contamination of stock DNA elutions, were stored at 4°C, and stock DNA elutions were stored at –20°C.

We started with a total of 320 bivalves (JTMD and Japanese samples) and used a PCR assay to test for amplifiable DNA. The primer set (jgLCO1490/jgHCO2198; Geller et al., 2013) amplifies the mitochondrial cytochrome oxidase I (COI) gene from a variety of mussel species. To screen for *Perkinsus* species, we used genus-specific primers (PerkITS85FNEW/PerkITS750R; Casas et al., 2002; Moss et al., 2007) that target the first internal transcribed spacer region (ITS1) of the ribosomal gene complex (rDNA). To screen for haplosporidian species, we used a general primer set (HAPF1/R3; Renault et al., 2000), which amplifies approximately 350 bp of one variable region of the small subunit of ribosomal RBA (SSU) gene and is capable of amplifying multiple genera (such as *Haplosporidium* sp., *Minchinia* sp., and *Bonamia* sp.) of haplosporidians. To screen for the presence of *Marteilia refringens,* we used a species-specific primer set (SS2/SAS1; Le Roux et al., 1999), which amplifies a portion of the SSU gene. To ensure that the PCR assays were amplifying the appropriate parasite DNA, positive control samples, consisting of extracted genomic DNA from infected bivalves that had successfully amplified in the past, were obtained from Dr. Ryan Carnegie for *M. refrigens* (Virginia Institute of Marine Science) and our own collection for *Perkinsus* sp. and haplosporidians.

Resulting sequences were edited using Sequencher 5.1 (Gene Codes Corporation, Ann Arbor, Michigan). To initially determine the organism detected, all sequences were subjected to a nucleotide search using BLAST[2] in GenBank against the nr (non-redundant) database for highly similar sequences. All duplicate sequences were concatenated prior to phylogeny constructions which contained only unique sequences that differed by one or more base pairs. To more accurately determine the organisms detected, phylogenetic reconstructions were made comparing the sequences from this study to haplosporidian sequences obtained from GenBank.[3]

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[2] http://blast.ncbi.nlm.nih.gov/
[3] http://www.ncbi.nlm.nih.gov/


Cathryn Clarke Murray

Results

JTMD objects analyzed

Six hundred and thirty-four objects were analyzed in whole or in part for the marine life attached to these objects (Carlton et al., 2017; Appendix 7-1). All JTMD items examined were from Alaska, British Columbia, Washington, Oregon, California, the Hawaiian Islands, and Midway Atoll. Most of them were acquired from British Columbia to California, and the Hawaiian archipelago. Objects included vessels, totes (crates, boxes, pallets, boxes), buoys (floats), cylinders, tanks, refrigerators, tires, and much more, including several Japanese trees (each with distinctive northeast Honshu marine life having been acquired after they entered the sea), post-and-beam wood ("beam" in figures, below), and two large docks from Misawa in Aomori Prefecture.

More than 70 vessels derived from the tsunami strike zone (including Aomori, Iwate, Miyagi, and Fukushima Prefectures) were sampled. Of approximately 55 vessels traced-to-source, nearly 85% were from Miyagi and Iwate Prefectures, in concert with the intensity of tsunami wave impact. The number of vessels detected vs. the number of vessels sampled was as follows: Alaska (17 detected/0 sampled), British Columbia (15/2), Washington (27/24), Oregon (35/30), California (4/2), and Hawaii (54/17). Thus, nearly 90% of all vessels that were detected in Washington and Oregon were sampled. More than 40 of the sampled vessels satisfied the criteria for JTMD-HR objects, as detailed in the Methods section.

Post-and-beam wood had a relatively short duration at sea: wood of this type first arrived in 2013, in agreement with general predictions that objects with no or little windage would require approximately 2 years to transit the North Pacific (see Chapter 2). The wood appeared to be largely gone by 2014, having thus been at sea for 2 to 3 years before extinction. This low persistence of wood was due to the infestation and effective destruction by wood-boring bivalve mollusks, the Teredinidae, or shipworms, of which no fewer than 8 species were detected (Treneman et al., 2018a, b; Appendix 7-3). Six of these species were from nearshore waters of the Western Pacific Ocean, whereas 2 species are members of the oceanic–pelagic community. Post-and-beam wood found on beaches after 2014 appeared to have either been ashore and undetected for more than a year, or were beached by storms somewhere in the North Pacific for a length of time and then subsequently refloated to resume their journeys to North America or the Hawaiian Islands.

Object arrival over time (Figure 7-1) had a relatively consistent pattern of spring pulse landings, with a cumulative curve indicating that overall, arrivals have not yet plateaued. The number of more easily verified larger object types (vessels, buoys, and totes) arriving has slowly decreased over time, but they continued to arrive as of February 2017. The two Port of Misawa docks that arrived on the Pacific coast of North America have been extensively referenced and discussed in many venues over the past 5 years. Four large docks used by the fishing industry in Misawa were present in the Port at the time the tsunami struck; all four were torn away, and went to sea. Three docks were detected at sea 10 days later, on March 21, about 80 km northeast of Tokyo (Figure 7-2). Misawa-1 (or JTMD-BF-1) landed on the central Oregon coast on June 5, 2012. Misawa-2 drifted past the Hawaiian Islands in September 2012, but was never seen again. Misawa-3 (JTMD-BF-8), landed on the coast of Washington State on December 18, 2012.

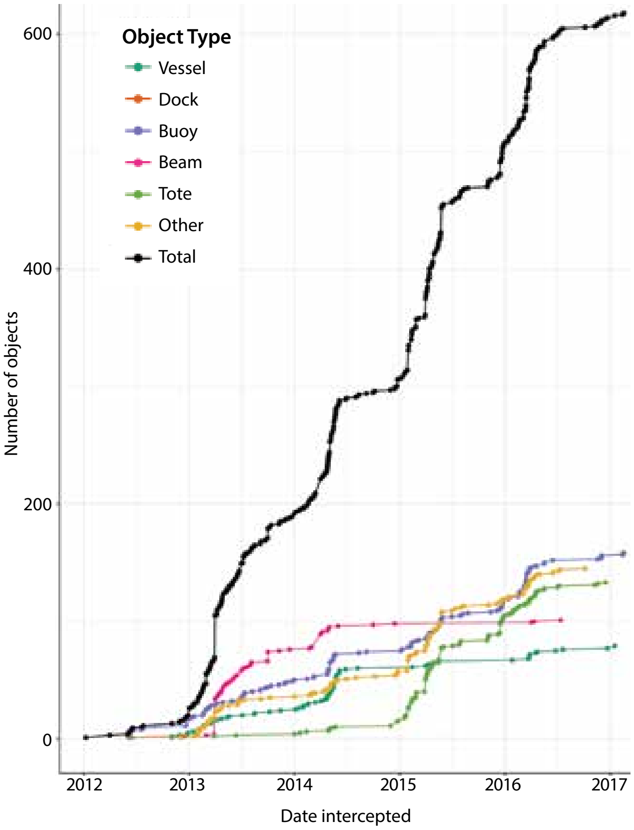
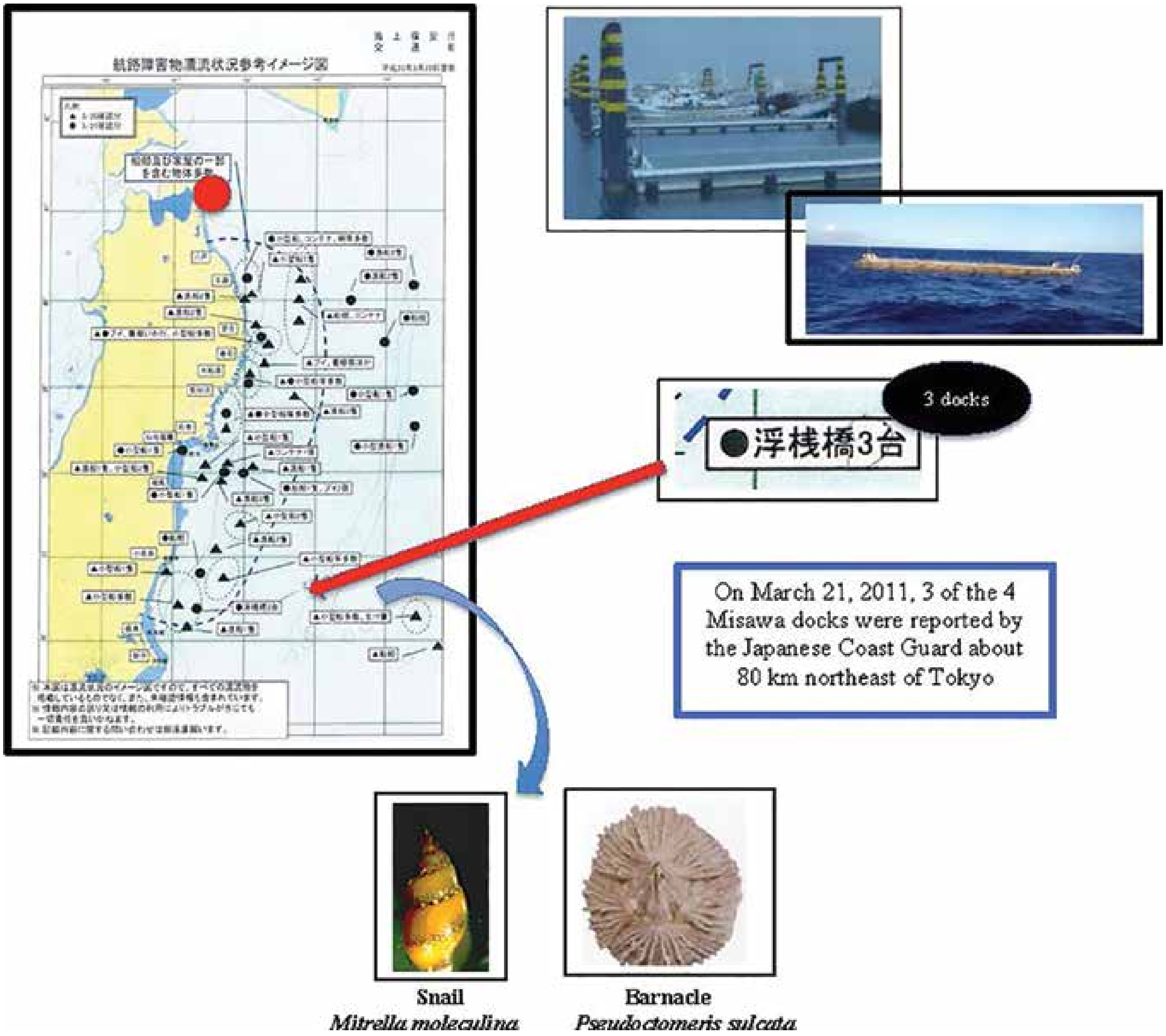


Figure 7-1. Cumulative arrivals of Japanese Tsunami Marine Debris (JTMD) objects over time. Post-and-beam wood pieces detected in 2016 represent re-drift (that is, wood washed back out to sea after earlier landings elsewhere), rather than being at sea continuously since 2011. Strong spring pulses of JTMD landings are evident. Figure from Carlton et al. (2017).



On March 21, 2011, 3 of the 4 Misawa docks were reported by the Japanese Coast Guard about 80 km northeast of Tokyo

Misawa 1 and *Misawa 3* arrived in North America with two living Japanese marine species found only south of the Boso Peninsula. Misawa 1 landed in Oregon on June 5, 2012 with the snail *Mitrella moleculina*. Misawa 3 landed in Washington on December 18, 2012 with the southern barnacle *Pseudoctomeris sulcata*. Neither *Mitrella moleculina* nor *Pseudoctomeris sulcata* appeared again on JTMD. Both species were acquired at around 35° N latitude or further south.

Mitrella	https://www.flickr.com/photos/80098236@N07/sets/72157630131187534
Pseudoctomeris	Yamaguchi and Hisatsune, 2006, Sessile Organisms 23: 1–15.

Figure 7-2. Location of three of the four Misawa docks on March 21, 2011, and the acquisition of southern signature species by Misawa-1 (JTMD-BF-1) and Misawa-3 (JTMD-BF-8) before departure to North America.


Nikolai Maximenko

JTMD biodiversity assessment

Nearly 300 Japanese species of marine animals have been detected on the debris field arriving in the Central and Eastern Pacific Ocean since the summer of 2012 (Carlton et al., 2017; Appendix 7-3). As noted in the Methods section, 80 taxonomists contributed to the resolution of this diverse biota. Genetic analyses contributed to resolving a number of species, including the difficult-to-distinguish large Asian marine mussel *Mytilus coruscus* (Appendix 7-3), as well as sponges, hydroids, bryozoans, shipworms, chitons, and fish (Table 7-1).

The fishing dock Misawa-1 arrived with more than 130 living species aboard, including microbiota, macroinvertebrates, and algae (seaweed). Six months later, Misawa-3 arrived with half that total diversity (66 species). Aboard Misawa-1 were 95 macro-invertebrate species; Misawa-3 arrived with 18 additional species not found on Misawa-1. Thus, Misawa-1 and Misawa-3 together arrived with over 100 species, or more than one-third of the total biota that was to arrive between 2012 and 2016. Remarkably, at least seven new species of marine life have been detected on JTMD (Table 7-2).

Table 7-1. Examples of molecular genetic contributions to Japanese Tsunami Marine Debris (JTMD) invertebrate and fish biodiversity (from Carlton et al., 2018).

Taxon		**JTMD sequence match (98% or better) to GenBank sequence from:**	**JTMD sequences (GenBank deposition numbers)**	**Reference**
Porifera (sponges)	*Halisarca "dujardini"**	White Sea (EU237483) and North Sea (HQ606143)	MG808392	Elvin et al., 2018
	*Haliclona xena**	The Netherlands (JN242209)	MG808391	Elvin et al., 2018
Hydrozoa (hydroid)	*Gonionemus vertens**	Japan, Russia, New England (numerous sequences)		Choong et al., 2018
	Eutima japonica	Japan (AB458489)		Calder et al., 2014
Bryozoa	*Bugulina stolonifera**	Galizia, Spain (KC129849-1)		McCuller and Carlton, 2018
	*Bugula tsunamiensis***	—	MF593127	McCuller, Carlton and Geller, 2018
Bivalvia: Teredinidae (shipworms)	*Bankia bipennata*	—	KY250360	Treneman et al., 2018a, b
	Bankia carinata	—	KY250355	
	Psiloteredo sp.	—	KY250324-29; KY250343-49	
	Teredothyra smithi	—	KY250357-59	
Polyplacophora (chitons)	*Mopalia seta*	Russia (EU407017, EU409069)	MG680054-58 MG680083-86	Eernisse et al., 2018
	Acanthochitona achates	—	MG677923-34 MG679991-6780001	
	Acanthochitona sp. A	—	MG79937-53 MG80003-80020	
	Acanthochitona rubrolineata	—	MG679935-36 MG680002	
Pisces: Carangidae (yellowtail jack)	*Seriola aureovittata*	Japan (numerous sequences)	MF069448–MF069455 MF0609456–MF069462	Craig et al., 2018

* detected in JTMD only as a DNA sequence.
** new species (see McCuller, Carlton and Geller, 2018 (*Aquatic Invasions* 13: 163-171).

Table 7-2. New species detected on Japanese Tsunami Marine Debris (JTMD) (from Carlton et al., 2018).

Taxon		Comments	Reference
Polyplacophora (chitons)	*Acanthochitona* n. sp.	Honshu and Ogasawara (Bonin) Islands	Eernisse et al., 2018
Ostracoda	*Sclerochilus* n. sp.		Tanaka et al., 2018
Bryozoa	*Bugula tsunamiensis*		McCuller et al., 2018
	Callaetea n. sp.		McCuller and Carlton, 2018
	Arbocuspis n. sp.		
Rhodophyta (red algae)	*Tsunamia transpacifica*	new genus and new species	West et al., 2016
	Stylonematophyceae, n. sp.	known as a DNA sequence	

Parasites in JTMD mussels

The parasitic hydroid *Eutima* sp. has been detected in 3.2% of the 1,158 mussels surveyed from JTMD objects. Infected mussels often exhibited high intensity of infection, with hundreds to thousands of hydroids on the gills of the host organisms (Figure 7-3). All cases to date were recorded on objects arriving in Oregon and Washington. No positive cases of the other two macroparasites, including pinnotherid crabs and the copepod *Mytilicola orientalis*, were detected among the mussels screened.

Eight mussels (3%) tested positive for haplosporidians on JTMD, of the 264 mussels screened to date. These were on JTMD objects that arrived in Oregon and Hawaii. It appears that these are novel lineages and cluster most closely to samples from South Africa and France (Hartikainen et al., 2014). Thus, the biogeography and identity of these protists are currently unknown. None of the 264 mussels tested positive for the other two protistan parasites, *Perkinsus* sp. or *Marteilia* sp.

Figure 7-3. The hydroid *Eutima* sp. from the inside of a mussel *Mytilus galloprovincialis* collected from JTMD arriving to North America. Image from Calder et al. (2014).

Macro-invertebrate biodiversity

Six groups accounted for nearly two-thirds of the invertebrate diversity (Figure 7-4): mollusks (bivalves, gastropods, and chitons), polychaetes (marine worms), cnidarians (hydroids and sea anemones), bryozoans (moss animals), crustaceans, and poriferans (sponges). In Figure 7-4, Annelida were primarily polychaetes, with the inclusion of rare oligochaetes, and Cnidaria included eight species of sea anemones and corals.

Cumulative species richness mirrored annual pulses of debris arrivals in spring (Figure 7-5). Overall cumulative diversity had not yet reached an asymptote as of February 2017, suggesting that total arriving diversity of macroinvertebrates was likely considerably larger. Carlton et al. (2017) provide further details on JTMD richness per object over time.

Eight invertebrate species were found on 35 or more objects (Table 7-3). More than 50% of all objects transported the large marine Mediterranean mussel *Mytilus galloprovincialis*, itself a 20th century invasion into Japanese waters. The Western Pacific encrusting marine bryozoan *Scruparia ambigua* was also very common, occurring on one-third of all objects.

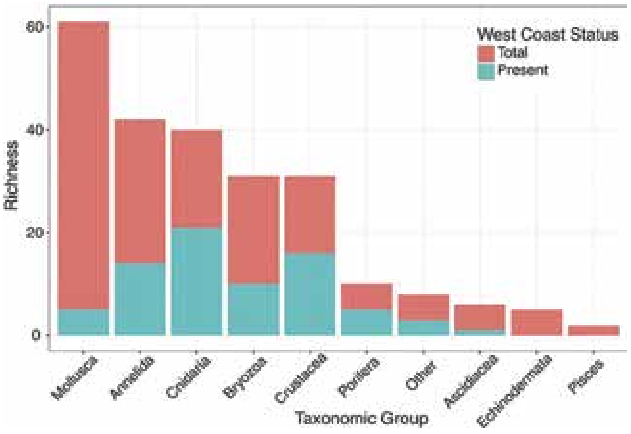


Figure 7-4. Living Japanese macro-invertebrate and fish species richness by taxonomic group. Number of species already present (due to natural distribution or previous introductions) on the Pacific coast of North America is in blue-green. "Other" taxa are Nemertea, Sipuncula, Insecta (Diptera), Pycnogonida, Acarina, and Kamptozoa. Figure from Carlton et al. (2017).

The acquisition and transport of southern biota

Adding to the expectation that a subset of the marine fauna and flora from the Tohoku coast would be transported by objects of both marine origin (already in the water at the time of the tsunami) and terrestrial origin (objects washed into the sea) is a guild of 40 adult species acquired by the debris from south of the Tohoku coast, during ocean rafting (Appendix 7-4). Besides, during the course of the debris history, native warm-water oceanic (neustonic) species were acquired, including the pelagic bryozoan *Jellyella eburnea* and the shipworm *Teredora princesae,* both species endemic to the little-known high seas drifting community.

These species appear to have largely settled as larvae as the debris drifted into more southern waters. While the possibility remains that the debris also became entangled and entwined with other rafted objects, and thus mobile or semi-mobile species may have transferred from co-rafted debris that was sourced elsewhere, the latter form a small group of only three species (an amphipod, a crab, and sea anemones). No northern, cold-water species, found only north and east of Hokkaido, arrived on JTMD in North America as adults, suggesting that the sojourn of JTMD in higher latitude waters was low prior to landing in the Eastern Pacific Ocean.

"Southern species" are defined as those whose known geographical distribution extends no further north than the Boso Peninsula. A number of species only occur as far north as the Kii Peninsula, while others occur north to the Amami Islands. However, no species were acquired that would suggest that any debris crossed the equator into the Southern Hemisphere. An early, but modest, signal of southern species acquisition was the appearance in 2012 of at least two warmer-water species on the docks Misawa-1 and Misawa-3 (see Figure 7-2). Critically, the number of southern species appearing on JTMD increased from 2012 (3 species), to 2013 (11 species), and 2014 and later (27 species). These results suggest that the debris continued to take a wider and longer circuitous path through lower latitudes of the North Pacific.

Table 7-3. Frequency of occurrence of eight most common living JTMD species (from Carlton et al., 2017).

Phylum	Class / Order	Species	Number of JTMD-BF items on which species were found alive (of 511 items with living biota)	Frequency of living individuals on JTMD-BF items (%)
Mollusca	Bivalvia	*Mytilus galloprovincialis*	261	51.1
Bryozoa	Cheilostomata	*Scruparia ambigua*	203	39.7
Bryozoa	Cheilostomata	*Aeteidae (Aetea anguina, Callaetea sp.)*	69	13.5
Arthropoda	Amphipoda	*Jassa marmorata*	45	8.8
Arthropoda	Isopoda	*Ianiropsis serricaudis*	39	7.6
Bryozoa	Cheilostomata	*Bugula tsunamiensis*	35	6.8
Arthropoda	Cirripedia	*Megabalanus rosa*	35	6.8

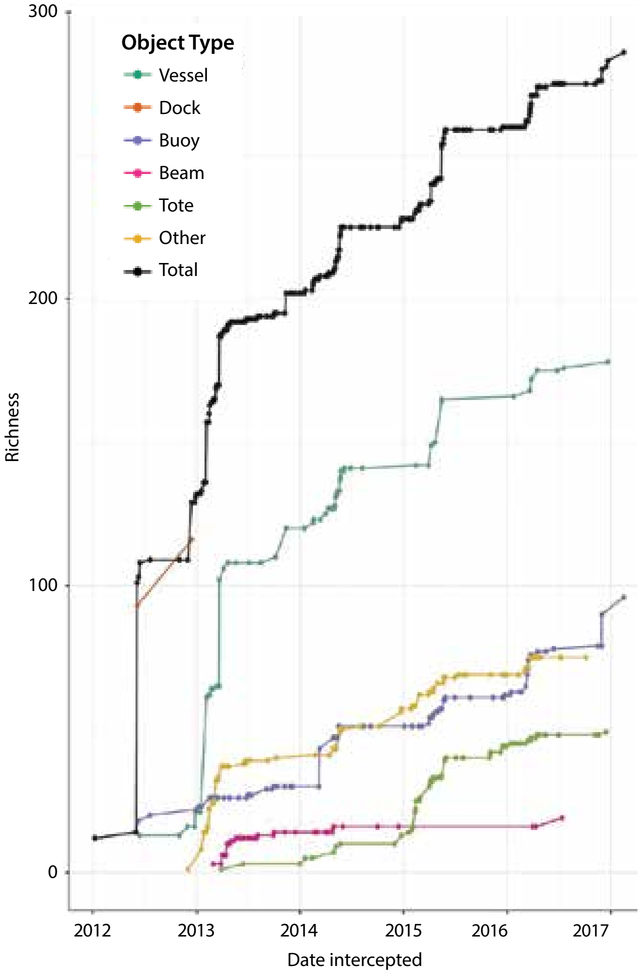


Figure 7-5. Cumulative Japanese living protist, invertebrate, and fish species richness by date and object type. Species accumulation for 289 taxa detected from Alaska to California and Hawaii from June 2012 to February 2017. Vessels are primarily skiffs ranging from 4 to 11.5 m in length; docks are JTMD-BF-1 and JTMD-BF-8, landing in central Oregon (June 2012) and northern Washington (December 2012), respectively; buoys are anchored or attached floats used in aquaculture, small harbors, and navigation; beams are post-and-beam timber (mortise-and-tenon construction) of standard Japanese dimensions; totes include crates, boxes, and cases used in fisheries and for domestic purposes; "other" includes pallets, pontoon sections, ropes, trays, propane tanks, carboys, items associated with the aquaculture and fisheries industries, and many other objects. Figure from Carlton et al. (2017).

Sea anemone species (Cnidaria: Anthozoa: Actiniaria)	**Location**	**2016**	**Object Southern Signature or Trajectory (see notes)**	**JTMD-BF**
Metridium dianthus	OR	3 March	1	524
Anthopleura asiatica	CA	5 March	3	504
Metridium dianthus *Diadumene lineata*	WA	7 March		509
Anthopleura asiatica	OR	16 March	3	522
Anthopleura asiatica	OR	16 March	3	634
Anthopleura asiatica	OR	22 March	2, 3, 4	526
Anthopleura asiatica	OR	24 March	1, 3	527
Anthopleura asiatica	OR	24 March	3	528
Anthopleura asiatica *Diadumene lineata* *Metridium dianthus*	OR	27 March	1, 2, 3	533
Anthopleura asiatica	OR	10 April	1, 3	649
Metridium dianthus	OR	15 April		537
Diadumene lineata	OR	16 April	2	538
Diadumene lineata	OR	18 April	2	543

Phase I:
Widespread landing over **896 km** from Oregon to California

Phase II:
Narrow landing over **287 km** from Central to Southern Oregon

Phase III:
Narrower landing over **198 km** from Central to South-Central Oregon

Southern signature or trajectory:

(1) Warm temperate - subtropical oceanic bryozoan *Jellyella eburnea* on debris object
(2) Warm temperate - subtropical neritic bivalves, bryozoans and/or coral on debris object
(3) Japanese sea anemone *Anthopleura* sp. (see text) on debris object
(4) Object observed moving along coast from south to north over 7-day period

Phase data:

I Salmon Creek Beach, Bodega Bay CA (March 5, BF504) to Gold Beach OR (March 3, BF524) to Long Beach WA (March 7, BF509)
II South Beach OR (16 March, BF522) to Gold Beach OR (26 March, BF558) to Lincoln City OR (27 March, BF533)
III Moolack Beach OR (10 April, BF649) to Sixes River OR (16 April, BF538) to Seal Rock (18 April, BF543)

Metridium dianthus
JTMD-BF-135
On a JTMD vessel
landed 17 February 2014
Yachats, Oregon
44°18′40″ N 124°6′17″ W

***Anthopleura* sp.**
JTMD-BF-504
On JTMD plastic debris
landed 5 March 2016
Bodega Bay, California
38°21′18″ N 123°4′4″ W

Diadumene lineata
JTMD-BF-543
On a JTMD buoy
landed 18 April 2016
Seal Rock, Oregon
44°29′57″ N 124°04′58″ W

Figure 7-6. A 47-day Spring 2016 JTMD debris and sea anemone landing event in North America.

Table 7-4. Examples of marine organisms arriving alive on JTMD in November and December 2016.

JTMD-BF-#	Object	Location	Landing date	Living Japanese species
661	black buoy	Hawaii: Hawaii Island: offshore South Kona, south of Honokohau Harbour	November 17, 2016	*Mytilus galloprovincialis* *Callaetea* sp. *Ianiropsis serricaudis* *Ianiropsis derjugini*
662	Kamilo Point blue crate	Hawaii: Hawaii Island: Kamilo Point	November 19, 2016	*Mytilus galloprovincialis*
663	blue tote fragment	Washington State: Long Beach Peninsula	November 8, 2016	*Mytilus galloprovincialis*
664	Long Beach turquoise buoy	Washington State: Long Beach Peninsula	November 30, 2016	*Mytilus galloprovincialis*
667	line and buoy mass from Japanese oyster farm	Hawaii: Kauai: Kapa'a	December 7, 2016	*Dendostrea folium* *Aglaophenia* sp. *Trypanosyllis zebra* *Actiniaria* sp. A *Scruparia ambigua* *Aeteidae* *Exochella tricuspis* *Crisia* sp. A *Entalophora* sp.?
675	vessel (5.5m) from Miyagi Prefecture (MG3-38403)	Hawaii: Oahu: Waimanalo	December 22, 2016	Actiniaria sp. B *Trachypleustes* sp. *Ampithoe* sp.

The spring 2016 sea anemone pulse

A remarkable JTMD landing event occurred in a 47-day episode between March 3 and April 18, 2016 when a pulse of sea anemones (Cnidaria: Anthozoa: Actiniaria) arrived with JTMD. These species originated from the warm waters of the Western Pacific Ocean, and the arrival included two species that had not been detected in the previous 4 years, and one species not seen since 2014 (Figure 7-6). These consisted of the Japanese warm-water anemone *Anthopleura* sp. and the cool-to-warm species *Diadumene lineata* and *Metridium dianthus* (the latter last arriving two years earlier). Thirteen objects were intercepted in this period, with combinations of one, two, or three of these species on the same object.

The event can be divided into three distinct phases. In Phase I, landings occurred between March 3 and March 7, over an approximately 900 km range from central California to southern Washington. In Phase II, landings occurred from March 16 to March 27, over a narrower range of nearly 300 km from central to southern Oregon. In Phase III, anemone-bearing debris arrived between April 10 and April 18, in an even narrower landing zone of about 200 km (Figure 7-6). Observation gaps prevented further fine-grained analysis of this curious pattern, as there was a largely unsurveyed area from central California to southern Oregon and, similarly, the northern coast of Washington and northward was largely unsurveyed as well.

The striking southern signature of these landings, in addition to the warm water *Anthopleura* sp. (a distinctive, eye-catching species with vertical rows of orange spots) was underscored by the simultaneous arrival in the same period (March 3 to April 18, 2016, on the four arrivals in Figure 7-6, and on an additional eight anemone-free objects) of a strong pulse of the subtropical–tropical pelagic bryozoan *Jellyella eburnea*. In a little under 7 weeks in spring 2016, this bryozoan arrived in the Pacific Northwest in the largest landing episode seen to date. In contrast, in the previous 6 months (between September 2015 and February 2016), *Jellyella eburnea* was detected on only two objects in the Pacific Northwest. Arriving in the same Phase II window in Oregon, on March 21 and March 25, 2016, respectively, were the tropical seasquirt *Herdmania pallida* (BF-523) and the tropical Indo-West Pacific crab *Sphaerozius nitidus* (BF-531), the latter represented by a male-female pair.

After April 18, 2016, landings of *Anthopleura* sp. and *Diadumene lineata* ceased as sharply as they had begun. It remains unclear as to how a debris field of widely disparate objects – from a small spray bottle cap to a vessel – and of a presumably significant potential range of windage could remain together in the North Pacific Ocean as a rafted conglomerate for a length of time sufficient to acquire the same species of sea anemones, move from the Western Pacific to the Eastern Pacific, and land in tightly sequential waves on the Pacific coast of North America. Of interest is that a short-term signal of *Anthopleura* arrival occurred again in the spring of 2017, as noted below.


Donna Pomeroy


John Chapman

JTMD with living Japanese species continued to arrive in 2017

Remarkably, JTMD with living Japanese species from the Tohoku coast continued to arrive in North America and the Hawaiian Islands as the close of Year 6 (2017) of the JTMD phenomenon approached (Table 7-4). While plastic debris may last in the oceans for decades, it remains unclear, as discussed above, what the long-term trajectory is relative to the open ocean survival of coastal species. Species detected arriving alive in late 2016 included the mussel *Mytilus galloprovincialis*, a suite of no fewer than six species of Japanese bryozoans, two species of yet-to-be-identified Asian sea anemones, two Japanese isopods (one, *Ianiropsis derjugini,* not previously detected), and other species. Particularly notable is the presence of living specimens of the distinctive Japanese oyster *Dendostrea folium* on a mass of line, buoys, and cultured oyster shells, derived from the oyster farms of the Tohoku coast, landing in December 2016 at Kapa'a, Kauai, Hawaiian Islands (a photograph of species from this line-buoy mass was on the cover of Science for September 29, 2017 (Carlton et al., 2017). Debris observers on Kauai with several decades experience reported that nothing similar had landed in more than 25 years of observations.

The most recent documentation of living Japanese invertebrates on JTMD arriving in the Central or Eastern North Pacific was in the spring of 2017 (Carlton et al., 2018). A JTMD orange plastic bucket (BF-688) with living mussels (*Mytilus galloprovincialis*) landed on March 2, 2017 on Long Beach, Washington. On March 9, 2017, a JTMD tray (BF-689) with living Japanese anemones (*Anthopleura* sp.) landed in Bandon, Oregon. A JTMD pulse arrived in the Hawaiian Islands in April–May 2017, including several objects landing on Kauai with Japanese anemones (JTMD-BF-691, 702, 705–711) and a JTMD black buoy (BF-696) found in the ocean off the Kona coast of the Big Island on May 11 with a living *M. galloprovincialis*. On April 27, a JTMD buoy (BF-693) landed on Long Beach, Washington with living Japanese limpets. Since that time and as of this writing (February 2018) no living Japanese species have been found on JTMD (including buoys, crates, totes, and vessels) arriving in Washington, Oregon, and Hawaii.

Discussion

Rafting of species with JTMD

The present work, initiated by funding through Oregon Sea Grant and the National Science Foundation, and continued for the 3 years through support by the Ministry of the Environment of Japan through the North Pacific Marine Science Organization (PICES), was the first to formally document the rafting of Western Pacific marine organisms across the North Pacific and their successful landing on the shores of the Hawaiian Islands in the Central Pacific and of North America in the Eastern Pacific.

We identified several parasites that arrived with JTMD on multiple occasions and locations, using the mussels *Mytilus* spp. as a model system. While it is not surprising that parasites (including commensals) were associated with JTMD invertebrates, since many taxa of parasites are known and often common in subtidal communities (e.g., Lauckner, 1983; Sinderman, 1990; Lafferty et al., 2006), this also underscores that parasites are a potent "multiplier," serving to increase the number of taxa associated with this vector. With our current sampling effort, we added three species associated with one host (*Mytilus* sp.), quadrupling the original number of detected taxa with further analysis. Thus, not only are the total number of invertebrate taxa detected on JTMD an underestimate – since many items went undetected and the biota were often undersampled on those detected – but parasite taxa are also largely overlooked in these estimates.

The parasite taxa detected are reported to have significant effects on host condition and survival. The hydroid *Eutima japonica*, which lives on the gills of mussels, scallops, and oysters, has been associated with extremely high juvenile mortality of infected bivalves (Kubota, 1992; Baba et al., 2007). Although the identity and biogeography of the detected haplosporidians are not known, other taxa in this group are known to cause disease and impact fishery species. Probably the best example is *Haplosporidium nelsoni* which occurs in the Japanese oyster *Crassostrea gigas* and was introduced to the eastern United States, causing widespread mortality of native oysters (Burreson et al., 2000; Burreson and Ford, 2004). Thus, while the detected parasites may cause severe pathology, and also appear to be generalists capable of infecting diverse taxa, the potential risks (effects) on North American taxa are not known.

What makes JTMD different from past ocean rafting and from other vectors?

Two enduring questions were consistently posed throughout the course of this research:

1. How does the modern rafting of marine debris with living organisms differ from "natural rafting"?
2. How does marine debris rafting, and in particular JTMD, differ from other anthropogenic vectors that did, do, and will continue to transport species from Japan to North America and Hawaii?

How does the modern rafting of marine debris with living organisms differ from "natural rafting"?

Historical rafting largely consisted of biodegradable materials such as trees, tree branches, and root masses. Little is known of this process as it applies to the transport of coastal species from Japan to Hawaii or to North America. There have been no reports in the literature of Western Pacific vegetation arriving with living Japanese species in either region, which suggests that such events, while not impossible, are likely rare. The deterioration and decomposition of post-and-beam wood in about a 2-year period, as observed in this study, advocates that wood is at risk of destruction in its high seas transit by marine wood-borers such as shipworms. In contrast, marine debris has added to the world's oceans long-lasting, non-biodegradable plastics, fiberglass, and other floating materials which appear to fundamentally differ from historic rafting materials in their at-sea longevity. That Western Pacific species have lasted, to date, for up to 5 years drifting in the North Pacific Ocean, implies that coastal species are able to survive long-term transoceanic dispersal events if provided more permanent rafts, but historically such events would have been limited by wood being unable to sustain their rafting integrity for lengthy periods of time.

How does marine debris rafting, and in particular JTMD, differ from other anthropogenic vectors that did, do, and will continue to transport species from Japan to North America and Hawaii?

JTMD rafting differs from the modern transport of marine life in both ship fouling communities and in ballast water by: (1) JTMD has a much slower at-sea transit speed (1 to 2 knots / 1.9–3.7 km h^{-1}) versus a typical commercial vessel speed(20 knots / 37 km h^{-1} or more), thus potentially effecting and impacting the development, adhesion, and retention of fouling communities; (2) JTMD has delivered extensive communities of adult organisms compared to planktonic stages of benthic and fouling species in ballast water, and (3) JTMD typically involves a one-way (unidirectional) arrival event, leading to the potential for living communities on debris, landing in shallow water, to have extended periods of time for reproduction and colonization compared to biofouled vessels residing in port for only hours or days.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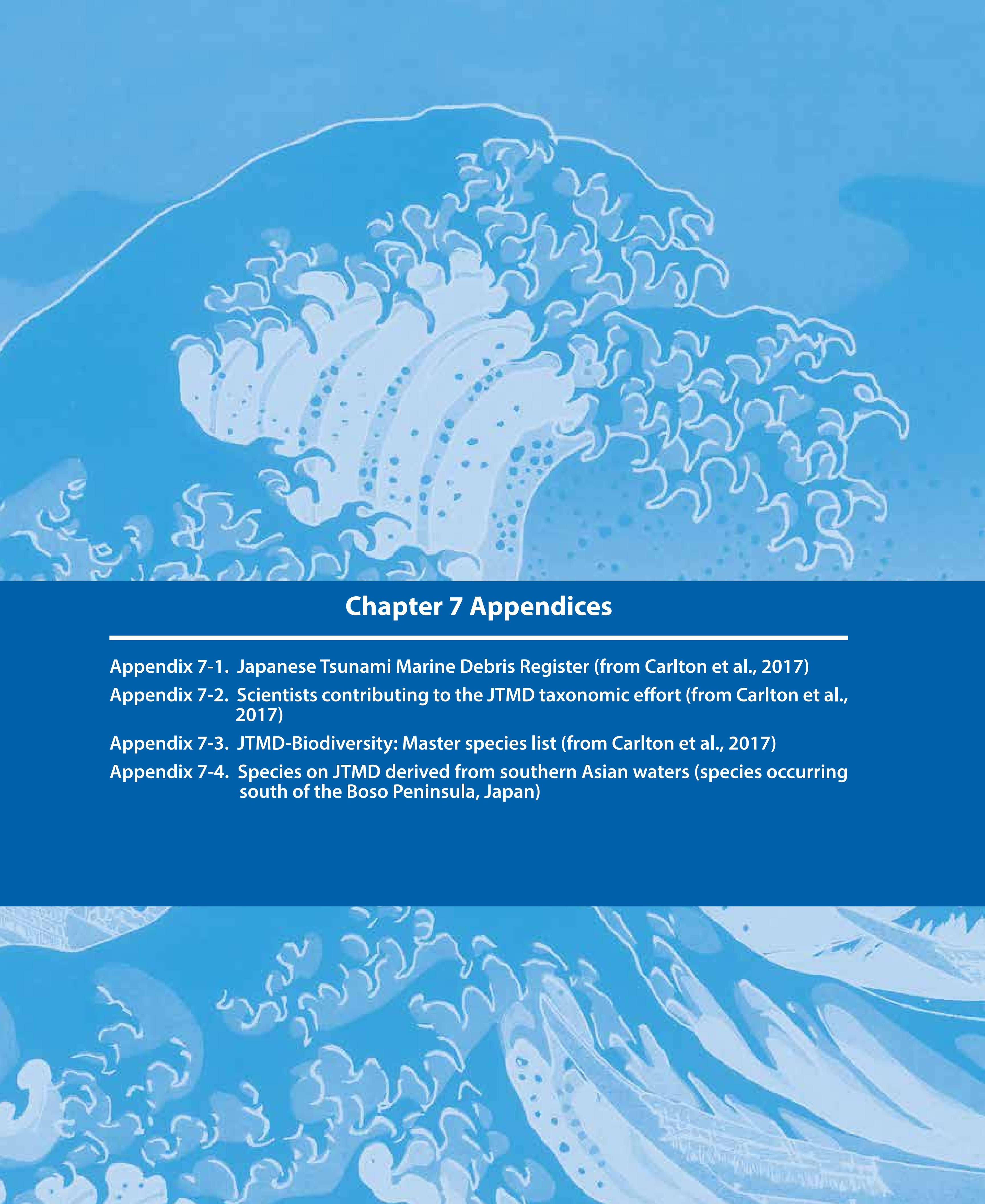

Chapter 7 Appendices

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017)

Appendix 7-2. Scientists contributing to the JTMD taxonomic effort (from Carlton et al., 2017)

Appendix 7-3. JTMD-Biodiversity: Master species list (from Carlton et al., 2017)

Appendix 7-4. Species on JTMD derived from southern Asian waters (species occurring south of the Boso Peninsula, Japan)

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
1*	OR	Agate Beach, near Newport	44.66455	-124.061158	Jun 5, 2012	dock	Aomori: Misawa
2*	WA	Ilwaco	46.302406	-124.037256	Jun 15, 2012	vessel	Miyagi
3*	OR	in ocean off Lincoln City	44.92825**	-124.045969 **	Jun 9, 2012	buoy	
4	OR	in ocean 85 km off Alsea Bay	44.418397	-124.922792	June 2012	buoy	
5	CA	Bodega Bay: Salmon Creek Beach	38.204659	-123.041335	Jun 19, 2012	float	
6*	HI	Oahu: Kahana Bay	21.556689	-157.874972	Nov 29, 2012	vessel	Iwate: Ofunato
7	OR	in ocean off Newport	44.614878 **	-124.195000 **	Jun 12, 2012	float	
8*	WA	Olympic National Park: near Mosquito Creek	47.798108	-124.482242	Dec 18, 2012	dock	Aomori: Misawa
9	WA	Olympic National Park: near Mosquito Creek	47.798108	-124.482242	Dec 20, 2012	float	
10	WA	Olympic National Park: near Mosquito Creek	47.798108	-124.482242	Dec 20, 2012	float	
11	HI	Oahu: Punaluu	21.591161	-157.890456	Dec 24, 2014	vessel	Miyagi
12	WA	Grays Harbor: Damon Point	46.931561	-124.100528	Dec 28, 2012	vessel	
13	WA	Olympic National Park: near Mosquito Creek	47.800236	-124.483256	Jul 20, 2012	buoy	
14	CA	16 km north of Fort Ross	38.596853	-123.350833	Apr 1, 2012	float	
15	CA	in ocean off Fort Ross	38.460178 **	-123.355556 **	Jul 26, 2012	buoy	
16	Midway	Eastern Island	28.205808	-177.336394	Nov 2, 2012	tote	
17*	HI	Oahu: Hanauma Bay	21.271094	-157.696808	Jan 9, 2013	buoy	
18*	OR	Clatsop Beach	46.188033	-123.989461	Jan 9, 2013	dock fender	
19	HI	Hawaii: Honokohau	19.676731	-156.026666	Jan 9, 2013	float	
20*	HI	Oahu: Mokuleia	21.582003	-158.206703	Jan 17, 2013	metal cylinder	
21	HI	Kauai: in ocean off Nohili Point	22.064383 **	-159.783819 **	Jan 18, 2013	navigation buoy	Fukushima: Onahama
22	WA	Ocean City State Park	46.983494	-124.174953	Feb 2, 2013	refrigerator	
23*	OR	Gleneden Beach	44.889214	-124.035278	Feb 5, 2013	vessel	
24*	OR	Newport: South Beach	44.607683	-124.0687	Feb 8, 2013	pallet	
25	HI	Oahu: Kahuku	21.683367	-157.944247	Feb. 13, 2013	vessel	Miyagi
27*	HI	Oahu: Makapuu Beach	21.311108	-157.66005	Feb 14, 2013	pontoon section	
28*	OR	Horsfall Beach	43.454106	-124.277689	Feb 20, 2013	vessel	Miyagi
29	OR	Clatsop Beach	46.188033	-123.989461	Feb 27, 2013	vessel	Iwate
30	OR	Lincoln City: Road's End	45.008075	-124.009661	Feb. 28, 2013	vessel	
31	HI	Oahu: Laie	21.648639	-157.922369	Mar 4, 2013	rope	
32*	HI	Maui: Ahihi Kinau	20.600631	-156.437	Mar 11, 2013	pontoon section	
33	HI	Oahu: Kahalu'u	21.457827	157.830000	Mar 7, 2013	buoy	
34	HI	Kauai: Lepeuli Beach	22.207492	-159.338625	Feb 20, 2013	ropes/buoys	
35	HI	Oahu: Kahuku	21.683367	-157.944247	Feb 21, 2013	buoy	
36	OR	Florence: Muriel Ponsler Wayside	44.169722	-124.117383	Mar 14, 2013	vessel	
37*	WA	Olympic National Park	47.798108	-124.482242	Mar 17, 2013	box	
38	OR	Cape Arago: Lighthouse Beach	43.338936	-124.372622	Mar 17, 2013	buoy	
39*	OR	Cannon Beach	45.892186	-123.964725	Mar 21, 2013	vessel	Fukushima
40*	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 22, 2013	vessel	Iwate: Rikuzentaka-ta
41	HI	Maui: Kahoolawe: Kanapou	20.546353	-156.553056	Mar 13, 2013	buoy	
42*	OR	Lincoln City: Salishan	44.889214	-124.035278	Apr. 9, 2013	log	
43*	OR	Lincoln City: Camp Westwind	45.038608	-124.006022	Apr 7, 2013	vessel	
44	BC	Ucluelet	48.9367	-125.552303	Mar 28, 2013	post-and-beam wood	
45	BC	Ucluelet	48.9367	-125.552303	2013	post-and-beam wood	
46	BC	Ucluelet	48.9367	-125.552303	Apr 8, 2013	post-and-beam wood	
47	OR	Nye Beach	44.642333	-124.063011	Apr 14, 2013	post-and-beam wood	
48	OR	Nye Beach	44.642333	-124.063011	Apr 14, 2013	post-and-beam wood	
49	HI	Oahu: Lanikai Beach	21.393008	-157.715328	Mar 29, 2013	container	
50*	OR	Coos Bay: north spit	43.411944	-124.300539	Apr 22, 2013	vessel	
51	OR	Coos Bay: north spit	43.411944	-124.300539	Apr 25, 2013	pallet	
52	OR	Coos Bay: north spit	43.411944	-124.300539	Apr 25, 2013	pallet	
53	BC	Ucluelet	48.9367	-125.552303	April 2013	post-and-beam wood	
54	HI	Hawaii: Kamilo Point Beach	18.974297	-155.597222	Apr 8, 2013	Float	
55	OR	Moolack Beach	44.699717	-124.0636	May 11, 2013	post-and-beam wood	
56	OR	Newport: South Beach	44.607683	-124.0687	Apr 17, 2013	tree	
57	OR	Newport: South Beach	44.607683	-124.0687	May 8, 2013	post-and-beam wood	
58*	OR	Clatsop Beach	46.188033	-123.989461	May 30, 2013	vessel fragment	
59	OR	Nye Beach	44.642333	-124.063011	May 30, 2013	post-and-beam wood	
60	OR	Tillamook Bay: Ocean Beach	45.561572	-123.952322	May 19, 2013	post-and-beam wood	
61	OR	Nye Beach	44.642333	-124.063011	May 30, 2013	post-and-beam wood	
63	WA	Grayland Beach North	46.805672	-124.105000	Apr 21, 2013	post-and-beam wood	
64	OR	Yaquina Head	44.675583	-124.077778	Jun 3, 2013	post-and-beam wood	
65	OR	between Lost Creek and Thiel Creek	44.552100	-124.075556	Jun 9, 2013	post-and-beam wood	
66	OR	between Lost Creek and Thiel Creek	44.552100	-124.075556	Jun 9, 2013	post-and-beam wood	
67*	OR	Cape Arago: North Cove	43.307539	-124.399283	Jun 18, 2013	pallet	
68	HI	Hawaii: Kamilo Point	18.974297	-155.597222	February 2013	refrigerator	
69	HI	Hawaii: Kamilo Point	18.974297	-155.597222	Mar 16, 2013	refrigerator	
70	HI	Hawaii: Kamilo Point	18.974297	-155.597222	Jun 23, 2013	TV set	
71*	WA	Olympic National Park	47.800236	-124.483256	Jun 23, 2013	pallet	
72	HI	Oahu: Punaluu	21.591161	-157.890456	Jun 17, 2013	I-beam	
73	OR	Coos County: Whiskey Run Beach	43.2163167	-124.396944	Jul 8, 2013	piling	
74	OR	Coos County: Whiskey Run Beach	43.2163167	-124.396944	Jul 8, 2013	post-and-beam wood	
75	HI	Oahu: Laie: Malaekahana Beach	21.668564	-157.936668	Jul 5, 2013	vessel	Iwate
76	AK	Kenai Fjords National Park	59.846864	-149.595081	Jun 24, 2013	buoy	
77	BC	Vancouver Is.: btwn Bamfield and Port Renfrew	48.627503	-124.771111	Jun 13, 2013	box	
78	WA	Makah Reservation	48.329967	-124.664167	May 12, 2013	vessel	Aomori
79	OR	Bandon region	43.115111	-124.436436	winter-summer 2013	buoy	
80	OR	Bandon	43.115111	-124.436436	winter-summer 2013	buoy	
81	OR	Bandon	43.115111	-124.436436	winter-summer 2013	pallet	

* = JTMD-HR: JTMD objects most thoroughly sampled (Higher Resolution) for macrobiota diversity.
OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017) (cont'd)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
82*	OR	Coos Bay region	43.216942	-124.396583	Mar 30, 2013	board	
83	BC	Vancouver Is.: Turret Is.	48.895589	-125.338889	May 18, 2013	plastic bottle	
84	HI	Oahu: James Campbell NWR	21.697456	-157.955556	week of July 8, 2013	buoy	
85	HI	Oahu: James Campbell NWR	21.697456	-157.955556	week of July 8, 2013	buoy with rope	
86	OR	North of Cape Sebastian: Kissing Rock	42.386447	-124.424722	Aug 4, 2013	post-and-beam wood	
87	HI	Oahu: Kawela	21.700403	-158.006547	Aug 14, 2013	vessel	Miyagi
88	HI	Oahu: Turtle Bay Resort	21.705314	-157.997778	Aug 17, 2013	vessel	
89	OR	Tillamook County: Bay Ocean Peninsula	45.561572	-123.952322	Jul 28, 2013	post-and-beam wood	
90*	HI	Hawaii: in ocean off Keauhou	19.575356 **	-155.991675 **	Sep 4, 2013	buoy	
91	HI	in ocean 1.6 km off Kona coast	19.341684	-155.585672	Sep 5, 2013	buoy	
92	HI	Hawaii: Kamilo	19.951283	-155.855347	Jul 12, 2013	buoy	
93	AK	Sitka area: SSSC/ Cherokee, Yamani area	56.669294	-135.197222	Aug 8, 2013	buoy	
94	BC	Ucluelet	48.9367	-125.552303	winter-spring 2013	vessel	
95	BC	Ucluelet area	48.9367	-125.552303	winter-spring 2013	vessel fragment	
96	HI	Maui: Au'au channel	20.780583	-156.73545	Sep 22, 2013	buoy	
97	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 20, 2013	post-and-beam wood	
103	OR	Bandon region	43.115111	-124.436436	late 2012 to early 2013	buoy	
104	OR	Bandon region	43.115111	-124.436436	late 2012 to early 2013	buoy	
105	OR	Bandon	43.115111	-124.436436	Jan 1, 2013	buoy	
106	OR	Cape Blanco	42.838236	-124.561644	Jul 11, 2013	buoy	
107	OR	Whiskey Run Beach	43.2163167	-124.396944	Jul 8, 2013	post-and-beam wood	
108	OR	Cape Arago: Lighthouse Beach	43.338936	-124.372622	Jul 11, 2013	post-and-beam wood	
109	OR	Cape Arago: Lighthouse Beach	43.338936	-124.372622	Jul 13 2013	post-and-beam wood	
110	BC	Ucluelet	48.9367	-125.552303	spring 2013	post-and-beam wood	
111	BC	Ucluelet	48.9367	-125.552303	spring 2013	post-and-beam wood	
114	OR	Rocky Point, south of Port Orford	42.719197	-124.467778	Jul 19, 2013	post-and-beam wood	
116	OR	Crook Point, south of Gold Beach	42.25125	-124.412772	Jul 1, 2013	post-and-beam wood	
117	OR	Brookings: Lone Ranch State Park	42.0982194	-124.343056	Aug 5, 2013	post-and-beam wood	
118	OR	Cape Arago: South Cove	43.303531	-124.396389	August 2013	post-and-beam wood	
119	OR	Pistol River, south of Gold Beach	42.277378	-124.408819	Apr 1, 2013	post-and-beam wood	
120	OR	North Cove, Cape Arago	43.307539	-124.399283	Apr 1, 2013	post-and-beam wood	
121	OR	Cape Arago: North Cove	43.307539	-124.399283	Apr 1, 2013	post-and-beam wood	
123	OR	Cape Arago: North Cove	43.307539	-124.399283	Apr 1, 2013	post-and-beam wood	
124	OR	Crook Point, south of Gold Beach	42.25125	-124.412772	Jul 1, 2013	post-and-beam wood	
125	OR	Lost Creek, south of Newport	44.551983	-124.073486	Oct 1, 2013	post-and-beam wood	
126	OR	Newport: Agate Beach	44.66455	-124.061158	Jul 1, 2013	post-and-beam wood	
127	OR	Crook Point, south of Gold Beach	42.25125	-124.412772	Jul 1, 2013	post-and-beam wood	
128	OR	Bandon	43.115111	-124.436436	Mar 2, 2014	post-and-beam wood	
129*	BC	Long Beach Peninsula	49.067658	-125.753644	Oct 6, 2013	vessel	
130*	OR	Clatsop Beach	46.188033	-123.989461	Oct 9, 2013	pontoon section	
131*	WA	Between Grayland Beach State Park and Tokeland	46.750892	-124.096014	Nov 13, 2013	vessel	
132	HI	Maui: Au'au channel between Maui and Lana'i	20.851781	-156.744167	Nov 27, 2013	buoy	
133	HI	Maui: Au'au channel between Maui and Lana'i	20.851781	-156.744167	Dec 4, 2013	buoy	
134*	WA	Westport: Twin Harbors State Park	48.857367	-124.108597	Jan 16, 2014	vessel	Miyagi
135*	OR	Yachats	44.335344	-124.099811	Feb 17, 2014	vessel	
136	OR	Newport: South Beach	44.607683	-124.0687	Feb 22, 2014	lid	
137	OR	Newport: South Beach	44.607683	-124.0687	Feb 22, 2014	post-and-beam wood	
138	HI	Kamilo Beach	18.974297	-155.597222	late January 2014	post-and-beam wood	
139*	HI	Pearl Harbor: Hickam Field	21.317361	-157.960361	Feb 18, 2014	vessel	Miyagi
140	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	December 2012	cooler	
141	WA	Long Beach Peninsula	46.475511	-124.071969	March 2013	lid	
142	HI	Oahu: Hanauma Bay	21.271094	-157.696808	May 29, 2013	buoy	
143	HI	Oahu: Kailua Beach	21.405117	-157.738383	Sep 6, 2013	pallet	
144	HI	Kauai: Waipake-Lepeuli	22.207492	-159.338625	Sep 29, 2013	buoy	
145	HI	Oahu: Maunalua Bay	21.258203	-157.744394	Oct 12, 2013	buoy	
147	HI	Kauai: Hanamaulu Beach Park	21.993161	-159.340833	Nov 8, 2013	lighted marine buoy	
148	HI	Maui: Kalepa Gulch: Waihee	20.935936	-156.506111	February 2014	vessel	
149	HI	Kauai: Waipake Beach	22.207492	-159.338625	Apr 27, 2013	buoy	
150	OR	Cape Arago: North Cove	43.307539	-124.399283	Oct 1, 2013	post-and-beam wood	
152	Midway	Eastern Island	28.205808	-177.336394	Nov 2, 2012	vessel	Miyagi
153	Midway	Eastern Island	28.205808	-177.336394	Feb 16, 2013	buoy	
154*	Midway		28.205808	-177.336394	2012-2013	buoy	
155	Midway	Eastern Island	28.205808	-177.336394	Feb 14, 2014	buoy	
156	Midway		28.205808	-177.336394	2012-2013	buoy	
157	OR	Newport: South Beach	44.607683	-124.0687	Oct 1, 2013	post-and-beam wood	
158	HI	Oahu: Malaekahana Beach Park	21.668564	-157.936668	Feb 12, 2014	box	
159	OR	Cape Arago: South Cove	43.303531	-124.396389	Jun 16, 2013	post-and-beam wood	
160*	OR	Cape Meares:Tillamook Bay spit	45.524289	-123.955261	Apr 26, 2014	tree	
161	OR	Newport: North Jetty	44.615053	-124.073889	Oct 1, 2013	post-and-beam wood	
163	OR	Otter Rock	44.746533	-124.062978	Oct 1, 2013	post-and-beam wood	
164	OR	Otter Rock	44.746533	-124.062978	Apr 5, 2014	post-and-beam wood	
165	OR	Ophir: Woodruff Creek	42.588292	-124.396944	May 2013	post-and-beam wood	
167	OR	Crook Point, south side	42.25125	-124.412772	Apr 1, 2013	post-and-beam wood	
168*	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 10, 2014	buoy	
170*	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 23, 2014	vessel	
171	OR	Tillamook	45.561572	-123.952322	Apr 25, 2014	post-and-beam wood	
172*	OR	Newport: South Beach	44.607683	-124.0687	Apr 27, 2014	buoy	
173*	OR	Newport: South Beach	44.607683	-124.0687	Apr 27, 2014	buoy	
174	OR	Yaquina Bay, beach at Hatfield Station	44.623867	-124.045278	Apr 26, 2014	post-and-beam wood	
176	OR	Newport: South Beach	44.607683	-124.0687	Apr 29, 2014	post-and-beam wood	

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JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
177*	WA	Ocean City State Park: Ocean Shores	46.983494	-124.174953	Apr 28, 2014	vessel	
179	BC	Ucluelet area: Salmon and Beach	48.9367	-125.552303	Mar 9/10, 2014	post-and-beam wood	
180	BC	Ucluelet area: Broken Group Islands	48.873264	-125.369445	Apr 8, 2014	post-and-beam wood	
181	WA	Long Beach Peninsula	46.475511	-124.071969	March 2013	buoy	
182	WA	Long Beach Peninsula	46.475511	-124.071969	March 2013	post-and-beam wood	
183	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 24, 2014	buoy	
184	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 24, 2014	buoy	
186	OR	Lost Creek, South Beach, 118th Street	44.551983	-124.073486	Apr 30, 2014	tote	
187	AK	Catherine Island, Chatham Strait	57.3224556	-134.812778	Apr 30, 2014	buoy	
188*	OR	Cape Lookout	45.356672	-123.973058	May 2, 2014	vessel	
189	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	buoy	
190	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	propane tank	
191	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	plastic fragment	
192	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	buoy	
193	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	buoy	
196*	OR	Waldport	44.439411	-124.084272	May 11, 2014	vessel	
197*	OR	Quinault	47.400867	-124.330544	May 9, 2014	pontoon section	
198*	OR	Sand Lake: Tierra del Mar	45.253539	-123.969358	May 12, 2014	vessel	
199*	OR	north of Umpqua River	43.783216	-124.174530	May 15, 2014	vessel	
200	OR	Rockaway: Manzanita State Park	45.720494	-123.945572	April 2012	buoy	
201*	OR	Brian Booth State Park	44.528783	-124.076225	May 16, 2014	vessel	
202*	OR	Surfland	44.580408	-124.069608	May 16, 2014	vessel	
203	WA	Long Beach Peninsula	46.475511	-124.071969	April 2013	buoy	
205*	HI	Kauai: Larsen's / Lepeuli Beach	22.206567	-159.338425	Apr 12, 2014	vessel	Miyagi
206	HI	Oahu: Waimanalo	21.328933	-157.689167	Apr 16, 2014	propane tank	
207*	OR	Coos Bay: Charleston	43.345911	-124.321667	May 17, 2014	buoy	
208*	OR	Cape Arago: North Cove	43.307539	-124.399283	May 19, 2014	vessel	
209*	HI	Oahu: Haleiwa, in ocean	21.810331 **	-158.317636 **	May 19, 2014	vessel	
210*	OR	Carter Lake	43.854247	-124.160867	May 21, 2014	vessel	
211	OR	Tahkenitch Lake region	43.805472	-123.169442	May 21, 2014	vessel	
212*	OR	Siuslaw River: South Jetty	44.015347	-124.139364	May 21, 2014	pontoon section	
214	OR	Cape Blanco	42.838236	-124.561644	Oct 1, 2013	post-and-beam wood	
215*	OR	South of Dunes City Tehakenitch campgrd beach	43.803047	-124.170392	May 19, 2014	buoy	
216*	OR	South of Dunes City Tehakenitch campgrd beach	43.803047	-124.170392	May 19, 2014	buoy	
217	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	buoy	
218	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	buoy	
219	OR	Cape Lookout Beach	45.356672	-123.973058	May 4, 2014	buoy	
221	OR	Cape Lookout Beach	45.356672	-123.973058	May 25, 2014	vessel	
222*	WA	Ocean Park	46.475511	-124.071969	May 23, 2014	vessel	Iwate
223*	WA	Long Beach Peninsula	46.475511	-124.071969	May 24, 2014	vessel	Miyagi
224*	WA	Long Beach Peninsula	46.475511	-124.071969	May 24, 2014	vessel	
225	OR	Strawberry Hill	44.254792	-124.112822	May 27, 2014	vessel	Iwate
226*	WA	Ocean City	46.983494	-124.174953	May 25, 2014	vessel	Miyagi
227*	WA	Long Beach Peninsula	46.475511	-124.071969	Jun 5, 2014	vessel	
228	WA	Long Beach Peninsula	46.475511	-124.071969	Jun 5, 2014	vessel	
229*	WA	Quinault	47.400867	-124.330544	Jun 6, 2014	vessel	Miyagi
230	WA	Long Beach Peninsula	46.475511	-124.071969	Jun 6, 2014	vessel	Miyagi
231	OR	South of Pistol River State Park	42.259853	-124.409167	Oct 1, 2013	post-and-beam wood	
232*	OR	Port Orford: Humbug Mountain State Park	42.687594	-124.448233	May 17, 2014	buoy	
233	OR	Netarts Bay	45.429753	-123.946803	Jun 28, 2014	vessel	
234	OR	Newport: South Beach	44.607683	-124.0687	Feb 9, 2013	propane tank	
235	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Mar 1, 2013	tire	
236	AK	Sitka	57.063358	-135.359564	May 25, 2014	buoy	
237*	AK	Sitka	57.063358	-135.359564	May 24, 2014	buoy	
239	AK	Sitka	57.063358	-135.359564	2013	buoy	
240*	CA	Daly City: Mussel Rock Beach	37.668644	-122.496175	Aug 9, 2014	vessel	
241*	OR	Cape Meares	45.524289	-123.955261	Aug 19, 2014	helmet	
242	HI	Maui: Au'au channel	20.851781	-156.744167	Sep 7, 2014	buoy	
244	BC	Ucluelet	48.9367	-125.552303	Apr 1, 2013	post-and-beam wood	
245	BC	Ucluelet	48.9367	-125.552303	Oct 1, 2013	post-and-beam wood	
246	BC	Ucluelet	48.9367	-125.552303	Jun 1, 2014	post-and-beam wood	
247	OR	Cape Arago: North Cove	43.307539	-124.399283	Dec 15, 2014	post-and-beam wood	
249	CA	Mendocino County: MacKerricher State Park	39.516656	-123.781389	Aug 13, 2014	buoy	
250	CA	Dry Lagoon	41.225081	-124.108608	Jun 6, 2014	vessel	Miyagi
251	BC	Ucluelet	48.9367	-125.552303	Apr 28, 2014	buoy	
252	OR	Cape Blanco north	42.838236	-124.561644	May 23, 2014	basket	
253	HI	Oahu: Kahana Bay	21.556536	-157.874844	Apr 22, 2014	vessel	Iwate
254	OR	Lost Creek	44.551983	-124.073486	Apr 29, 2014	tote	
255*	WA	Ocean Shores	46.972447	-124.176611	May 7, 2014	tote	
257	HI	Oahu: between Sandy Beach and Erma's	21.289992	-157.665069	Oct 6, 2014	pontoon section	
258*	OR	Seal Rock: Quail Street	44.414208	-124.083808	Feb 23, 2013	container box doors	
259	OR	Bay Ocean	45.520389	-123.95667	February 2013	carboy	
260	OR	Retz Creek: south of Port Orford	42.712125	-124.461944	Mar 11, 2013	wooden dock frame	
261	OR	Gold Beach: Kissing Rock	42.386447	-124.424722	Apr 1, 2013	Post & Beam wood	
262	OR	Bandon	43.115111	-124.436436	Apr 1, 2013	post-and-beam wood	
263	OR	Crooked Creek, Bandon (Devil's Kitchen State Park)	43.0818833	-124.437222	Apr 1, 2013	milled log	
264*	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Dec 22, 2014	tree	
265	OR	Newport: Moolack Beach	44.699717	-124.0636	Apr 1, 2014	post-and-beam wood	
266	OR	Newport: Moolack Beach	44.699717	-124.0636	Apr 1, 2013	post-and-beam wood	
267	OR	Newport: Moolack Beach	44.699717	-124.0636	Apr 1, 2013	post-and-beam wood	

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OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017) (cont'd)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
269	OR	Newport: Moolack Beach	44.699717	-124.0636	Apr 1, 2014	post-and-beam wood	
271	OR	Newport: Moolack Beach	44.699717	-124.0636	Apr 1, 2014	post-and-beam wood	
272	OR	Newport: Moolack Beach	44.699717	-124.0636	Apr 1, 2014	post-and-beam wood	
274	OR	Newport: South Beach	44.607683	-124.0687	Apr 1, 2013	post-and-beam wood	
277*	OR	Seal Rock	44.414208	-124.083808	Nov 30, 2014	tote	
280	OR	Lincoln City: Road's End	45.008075	-124.009661	Apr 1, 2014	post-and-beam wood	
281	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	May 8, 2014	carboy	
282*	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	May 8, 2014	milled wood	
283*	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	May 8, 2014	buoy	
284	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 23, 2014	buoy	
285	WA	Long Beach Peninsula	46.475511	-124.071969	Jan 4, 2015	vessel	
286	WA	Long Beach Peninsula	46.475511	-124.071969	January 2015	fillet board	
287	WA	Long Beach Peninsula	46.475511	-124.071969	January 2015	tote	
288*	OR	Beverly Beach	44.7199	-124.059308	Jan 20, 2015	pallet	
289	OR	Tillamook: South Jetty Beach (north of Cape)	45.561572	-123.952322	Jan 18, 2015	tote	
290	OR	Tillamook	45.561572	-123.952322	Jan. 18, 2015	tote	
291	OR	Tillamook: South Jetty Beach (north of Cape)	45.561572	-123.952322	Jan. 18, 2015	tote	
292	WA	Tokeland	46.704481	-123.974444	Jan 20, 2015	tote	
293*	WA	Long Beach Peninsula	46.475511	-124.071969	Jan 28, 2013	pipe	
295	WA	Long Beach Peninsula	46.475511	-124.071969	Jan 27, 2015	sieve lid	
296	OR	Bandon: Bullard's Beach	43.152231	-124.415278	Apr 1, 2013	post-and-beam wood	
297	OR	Bandon: Bullard's Beach	43.152231	-124.415278	Apr 1, 2013	post-and-beam wood	
298	OR	Bandon: Bullard's Beach	43.152231	-124.415278	Apr 1, 2014	post-and-beam wood	
299	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 11, 2015	tote	
300	WA	La Push: Toleak Point	47.833653	-124.539722	Feb 10, 2015	buoy	
301	WA	La Push: Strawberry Point	47.845478	-124.550000	Feb 11, 2015	buoy	
302	WA	La Push: Strawberry Point	47.845478	-124.550000	Feb 11, 2015	buoy	
303	WA	La Push: Strawberry Point	47.845478	-124.550000	Feb 11, 2015	buoy	
304*	OR	in ocean off Newport	44.634933 **	-124.211486 **	Feb 12, 2015	basket	
305*	OR	Lincoln City: Westwind Camp	45.038608	-124.006022	Feb 13, 2015	crate	
306*	OR	Brookings	42.043511	-124.268592	Feb 10, 2015	tote	
309	OR	Cape Arago: South Cove	43.303531	-124.396389	Apr 1, 2013	post-and-beam wood	
311	HI	Oahu: Waimanalo Beach	21.328933	-157.689167	Apr 1, 2013	post-and-beam wood	
312	HI	Oahu: Waimanalo Beach	21.328933	-157.689167	Apr 1, 2013	post-and-beam wood	
313	HI	Kauai: Donkey Beach	22.115622	-159.296389	Apr 1, 2014	post-and-beam wood	
315	HI	Kauai: Hanamaulu Beach	21.993161	-159.340833	Nov 9, 2013	post-and-beam wood	
316	WA	Moclips	47.229131	-124.216706	Apr 1, 2013	post-and-beam wood	
317	WA	Moclips	47.229131	-124.216706	Apr 1, 2013	post-and-beam wood	
318	WA	Moclips	47.229131	-124.216706	2013-2014	post-and-beam wood	
321	WA	Grayland	46.805672	-124.105000	spring 2014	post-and-beam wood	
322	WA	Queets	47.540406	124.3568	October 2014	post-and-beam wood	
323	WA	Ocean Shores	46.972447	-124.176611	spring 2014	post-and-beam wood	
327	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	spring 2013	milled log	
328*	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tray	
329*	HI	Hawaii: Kohanaiki	19.694592	-156.044561	Feb 14, 2015	vessel	Miyagi
330*	WA	Strawberry Point	47.845822	-124.550458	Feb 25, 2015	buoy	
331	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Mar 14, 2014	vessel	
332	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	lid	
333	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	pot	
334	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	urchin tray	
335	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	sieve	
336	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	buoy	
337	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	pipe	
338*	WA	Olympic National Park	47.798108	-124.482242	May 22, 2015	pallet	
339*	WA	Olympic National Park	47.798108	-124.482242	May 16, 2015	vessel	
340	BC	Wouwer Island: Beach	48.898867	-125.33145	Mar. 29, 2015	pallet	
341*	WA	Olympic National Park	47.798108	-124.482242	May 22, 2015	buoy	
342	WA	Olympic National Park	47.798108	-124.482242	May 22, 2015	buoy	
343	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tote	
344	OR	Cape Perpetua	44.290814	-124.112208	Apr 7, 2015	tote	
345	WA	Long Beach Peninsula	46.475511	-124.071969	December 2014	frame	
346	WA [not HI]	Waikiki Beach	46.278106	-124.07865	Apr 1, 2015	tote	
347*	OR	Seal Rock	44.414208	-124.083808	Apr 14, 2015	buoy	
348	OR	Seal Rock	44.414208	-124.083808	Apr 14, 2015	buoy	
349*	WA	Copalis Beach	47.116217	-124.184644	Apr 14, 2015	tank	
350	WA	Moclips	47.229131	-124.216706	Apr 14, 2015	sieve	
352*	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 30, 2015	vessel	
353	WA	Moclips	47.229131	-124.216706	Apr 5, 2015	tote	
354	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 3, 2015	tote	
355	WA	Roosevelt Beach, Moclips	47.1722	-124.19536	Apr 6, 2015	tote	
356*	OR	in ocean off Seal Rock	44.517033**	-124.1203**	Apr 9, 2015	vessel	Iwate
357	WA	Ocean Shores	47.53138	-124.353	2012 to pre-April 2015	buoy	
358*	WA	Olympic National Park: Queets	47.540406	124.3568	Apr 9, 2015	tray	
359	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 13, 2015	tote	
360	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 25, 2015	tote	
361	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 25, 2015	tote	
362	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Jul 29, 2015	tote	
363*	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Feb 26, 2015	bowl	
364	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	May 8, 2015	carboy	
365	WA	Ocean Shores	46.972447	-124.176611	Jul 5, 2015	tote	

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OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017) (cont'd)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
366	WA	Kayostia Beach	48.037831	-124.68265	Jul 15, 2015	boom	
367*	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Jul 29, 2015	tote	
368	WA	Long Beach Peninsula	46.475511	-124.071969	May 18, 2015	lid	
369*	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
370	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	rebar cap	
371	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	eel trap	
372	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
373	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
374	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
375	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	top	
376	WA	Long Beach Peninsula: Seaview	46.475511	-124.071969	May 25, 2015	tote	
377	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	pan	
378	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
379	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
380	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
382*	CA	San Francisco: Ocean Beach	37.759711	-122.511564	May 26, 2015	tote	
383	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tote	
384	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 25, 2014	tote	
386*	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	buoy	
387*	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 25, 2014	frame	
388*	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 25, 2014	tote	
389	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 25, 2014	tote	
390	WA	Long Beach Peninsula	46.475511	-124.071969	January-March 2015	propeller	
391	WA	Long Beach Peninsula	46.475511	-124.071969	January-March 2015	cylinder	
392	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	cutting board	
393	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tub	
395	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	crate	
396	WA	Moclips	47.229131	-124.216706	Apr 14, 2014	pallet	
397	WA	Long Beach Peninsula	46.475511	-124.071969	May 1, 2015	pontoon section	
398	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	octopus trap	
400	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	mirror cover	
401	WA	Kalaloch Beach	47.605564	-124.378775	Aug 7, 2015	buoy	
402*	WA	Seaview	46.475511	-124.071969	May 10, 2015	vessel	
403	WA	Kalaloch	47.605564	-124.378775	Apr 25, 2015	buoy	
404	OR	Kissing Rock Beach	42.386447	-124.424722	Aug 25, 2015	buoy	
405*	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tote	
406*	WA [not HI]	Waikiki Beach	46.278106	-124.07865	March-April 2015	tote	
407	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	bucket	
408	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tote	
409	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tote	
410*	OR	open ocean off Newport	44.576869	-124.695656	Feb 10, 2015	tote	
411	OR	open ocean off Newport	44.576869	-124.695656	Feb 10, 2015	tote	
412	WA	Long Beach Peninsula	46.475511	-124.071969	March-April 2015	tote	
413	WA	Long Beach Peninsula	46.475511	-124.071969	January-March 2015	tote	
414*	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 14, 2014	tote	
415	WA	Long Beach Peninsula	46.475511	-124.071969	January-February 2015	plastic fragment	
416	OR	Newport: South Beach	44.607683	-124.0687	spring 2013	milled log	
417	OR	open ocean off Newport	44.576869	-124.695656	Feb 25, 2015	tote	
418	WA	Long Beach Peninsula	46.475511	-124.071969	May 26, 2015	tote	
420	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	May 26, 2015	vessel panel	
421	HI	Kauai: Kealia Point	22.090506	-159.304722	Apr 1, 2014	post-and-beam wood	
422	OR	Bandon	43.115111	-124.436436	Dec 15, 2013	post-and-beam wood	
423	OR	Gold Beach: Barley Beach	42.456883	-124.423803	May 14, 2015	pallet	
424	OR	Crook Point, south of Gold Beach	42.25125	-124.412772	Mar 28, 2015	tote	
425	OR	Crook Point	42.25125	-124.412772	Apr 17, 2015	golf caddy leg	
426	WA	Queets	47.540406	-124.3568	Apr 9, 2015	tray	
427	OR	Cape Arago	43.307539	-124.399283	May 28, 2015	plastic bar	
428	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Apr 11, 2015	buoy	
429	WA	Queets	47.540406	-124.3568	Apr 9, 2015	tray	
430	WA	Ocean Shores	47.53138	-124.353	2014	tray	
433	OR	Kissing Rock Beach, south of Gold Beach	42.386447	-124.424722	Dec 16, 2014	bucket	
434	CA	Bodega Bay: Doran Spit	38.311311	-123.047500	Apr 1, 2013	post-and-beam wood	
435	WA	Long Beach Peninsula (Surfside and north)	46.475511	-124.071969	Nov 4, 2015	bin	
436	WA	Long Beach Peninsula: north of Oysterville approach	46.551036	-124.061892	Nov 5, 2015	tray	
437	WA	Long Beach Peninsula: Oysterville	46.551036	-124.061892	Nov 5, 2015	tote	
438	WA	Long Beach Peninsula	46.475511	-124.071969	May 8, 2015	buoy	
439	WA	Long Beach Peninsula	46.475511	-124.071969	May 29, 2015	buoy	
440	OR	Beverly Beach	44.7199	-124.059308	Dec 16, 2015	buoy	
441	OR	Bandon: 3.2 km south of Coquille Point	43.108092	-124.436389	week of Nov. 2, 2015	tote	
442	WA	Long Beach Peninsula	46.475511	-124.071969	Nov 14, 2015	buoy	
443	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 9, 2015	tote	
444	WA	Long Beach Peninsula	46.475511	-124.071969	2015	tote	
445	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 15, 2015	buoy	
446	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 17, 2015	tote	
447	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 22, 2015	tote	
448	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Dec 22, 2015	rope/tote	
449*	WA	Moclips	47.229131	-124.216706	May 29, 2014	vessel	
451	OR	Nye Beach	44.642333	-124.063011	Dec 26, 2015	buoy	

* = JTMD-HR: JTMD objects most thoroughly sampled (Higher Resolution) for macrobiota diversity.

OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017) (cont'd)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
452	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 24, 2015	buoy	
453	HI	Oahu: Waimanalo	21.328933	-157.689167	Apr 1, 2014	post-and-beam wood	
454	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	Styrofoam-wood panel	
455*	WA	Copalis Beach	47.116217	-124.184644	Apr 3, 2015	buoy	
456	OR	Bandon	43.115111	-124.436436	Dec 20, 2015	tote	
457	OR	Manzanita	45.720494	-123.945572	Feb 28, 2015	tote	
458*	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 15, 2015	fish box	
459	WA	Ocean Shores	46.972447	-124.176611	Dec 4, 2015	buoy	
460	WA	Ocean Shores	46.972447	-124.176611	Dec 4, 2015	plastic fragment	
461	OR	Manzanita	45.720494	-123.945572	Feb 28, 2015	tote	
462	WA	Long Beach Peninsula	46.475511	-124.071969	Jan 4, 2015	buoy	
463	WA	Queets	47.540406	-124.3568	Apr 9, 2015	tray	
464	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
465	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
466	OR	Queets	47.540406	-124.3568	Jan 23, 2015	tote	
467	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	tote	
468	WA	Long Beach Peninsula: 4.8 km north of Oysterville	46.551036	-124.061892	Mar 13, 2014	pallet	
469	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
470	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
471	WA	Queets	47.540406	-124.3568	Dec 16, 2015	line	
472	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
473	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
474	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
475	WA	Queets	47.540406	-124.3568	Dec 16, 2015	tote	
476	WA	Long Beach Peninsula: near Leadbetter Point	46.475511	-124.071969	Dec 25, 2015	tote	
477	WA	La Push to Kalaloch	47.605564	-124.378775	May 10, 2015	buoy	
478	WA	La Push to Kalaloch	47.605564	-124.378775	May 24, 2015	buoy	
479	WA	La Push to Kalaloch	47.605564	-124.378775	May 24, 2015	buoy	
480	WA	La Push to Kalaloch	47.605564	-124.378775	July 2015	buoy	
481	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 23, 2015	buoy	
482	WA	Roosevelt Beach, Moclips	47.229131	-124.216706	2015	rope	
483	OR	Cape Lookout	45.36350	-123.97057	Apr 1, 2014	post-and-beam	
485	WA	Long Beach Peninsula: Oysterville	46.63135	-124.07090	Apr 1, 2013	post-and-beam	
486	WA	Long Beach Peninsula: Oysterville	46.63135	-124.07090	Apr 1, 2013	post-and-beam	
487	WA	Long Beach Peninsula: Oysterville	46.63135	-124.07090	Apr 1, 2013	post-and-beam	
488	WA	Long Beach Peninsula: Oysterville	46.63135	-124.07090	Apr 1, 2013	post-and-beam	
489	WA	Long Beach Peninsula: Oysterville	46.63135	-124.07090	Apr 1, 2013	post-and-beam	
493	WA	Long Beach Peninsula: Oysterville	46.63135	-124.07090	Apr 1, 2014	vessel panel	
494	OR	Gold Beach: Pistol River	42.277378	-124.408819	Apr 1, 2013	post-and-beam	
495	OR	Bandon	43.115111	-124.436436	May 22, 2014	wood-metal fragment	
496	WA	Long Beach Peninsula	46.475511	-124.071969	Jan 29, 2016	tote	
497*	HI	Oahu: Laie	21.648594	-157.921944	Jan 25, 2016	vessel	Aomori
498	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 11, 2016	tote	
499	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 15, 2016	buoy	
500	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 16, 2016	tote	
501	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 18, 2016	tree	
502	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 20, 2016	buoy	
503	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 20, 2016	buoy	
504	CA	Bodega Bay: Salmon Creek Beach	38.324833	-123.0728	Mar 5, 2016	plastic cap	
505	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 7, 2016	buoy	
506	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Mar 7, 2016	buoy	
507	OR	Tillamook Bay: Bay Ocean Peninsula	45.561572	-123.952322	Mar 7, 2016	buoy	
508	OR	Arch Cape	45.816578	-123.964722	Feb 19, 2016	tote	
509	WA	Long Beach Peninsula	46.475511	-124.071969	Mar. 7, 2016	buoy	
510	WA	Ocean Shores	47.53138	-124.353	2012-2015	buoy	
511	WA	Ocean Shores	47.53138	-124.353	2012-2015	buoy	
512	WA	Ocean Shores	46.972447	-124.176611	between 2012 &2015	buoy	
513	OR	Gold Beach: Kissing Rock	42.362	-124.42448	Dec 21, 2015	buoy	
514	OR	Tillamook	45.561572	-123.952322	Jan 16, 2016	buoy	
515	OR	Bandon	43.115111	-124.436436	Dec 22, 2015	buoy	
516	OR	Tillamook: South Jetty	45.561572	-123.952322	Jan 16, 2016	plastic bar	
517	OR	Cape Blanco, south near Eel River	42.82883	-124.5506	Dec 28, 2015	tote	
518	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 14, 2016	buoy	
519	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 7, 2016	container	
520	OR	Tillamook Bay: Bay Ocean Peninsula	45.561572	-123.952322	Mar 14, 2016	buoy	
521*	OR	Nye Beach	44.642333	-124.063011	Mar 14, 2016	tote	
522	OR	Newport: South Beach	44.607683	-124.0687	Mar 16, 2016	buoy	
523	OR	Gold Beach: Pistol River	42.277378	-124.408819	Mar 21, 2016	shoe	
524	OR	Gold Beach: Myers Creek Beach	42.311950	-124.416389	Mar 3, 2016	broom handle	
525	OR	Yachats	44.335344	-124.099811	Mar 16, 2016	dust pan	
526*	OR	Horsfall Beach	43.454106	-124.277689	Mar 22, 2016	vessel	
527	OR	Hubbard creek	42.735542	-124.478703	Mar 24, 2016	pot	
528	OR	Hubbard creek	42.735542	-124.478703	Mar 24, 2016	tray	
529	OR	Hubbard creek	42.735542	-124.478703	Mar 24, 2016	buoy	
530	OR	Hubbard creek	42.735542	-124.478703	Mar. 24, 2016	vessel	
531*	OR	Seal Rock: Quail Street	44.483056	-124.084503	Mar 25, 2016	buoy	

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OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017) (cont'd)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
532*	WA	Kalaloch	47.6019	-124.375589	Mar 26, 2016	vessel	Iwate
533*	OR	Lincoln City: Road's End	45.008075	-124.009661	Mar 27, 2016	vessel	
534	OR	Long Beach Pen: 3.2km south of Leadbetter Pt.	46.475511	-124.071969	Mar 25, 2016	tote	
535	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 3, 2016	rope	
536	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 5, 2016	tote	
537	OR	South of Winchester Bay	43.646717	-124.213056	Apr 15, 2016	tote	
538*	OR	Sixes River	42.855417	-124.543953	Apr 16, 2016	vessel	
539	HI	Kauai: Kealia Beach	22.090506	-159.304722	Apr 1, 2013	milled log	
540	HI	Kauai: Kealia Beach	22.090506	-159.304722	Apr 1, 2013	milled log	
541	WA	Long Beach Peninsula	46.475511	-124.084503	Apr 15-17, 2016	tote	
542	WA	Long Beach Peninsula	46.475511	-124.084503	Apr 12, 2016 [re-drift]	post-and-beam wood	
543	OR	Seal Rock: Quail Street	44.483056	-124.084503	Apr 18, 2016	buoy	
544	OR	Seal Rock Quail Street beach	44.483056	-124.084503	Apr 18, 2016	dish rack	
545	OR	mouth of the Umpqua River	43.667692	-124.214722	Mar 26, 2016	vessel	
546	OR	Moolack Beach Bridge	44.699717	-124.0636	Apr 29, 2016	barrel fragment	
547	WA	Long Beach Peninsula	46.475511	-124.071969	May 14, 2016	tote	
548	WA	Long Beach Peninsula	46.475511	-124.071969	May 16/17, 2016	buoy	
549	WA	Long Beach Peninsula	46.475511	-124.071969	May 16, 2016	tote	
550	WA	Long Beach Peninsula	46.475511	-124.071969	May 16, 2016	buoy	
551	WA	Long Beach Peninsula	46.475511	-124.071969	Sep-Dec 2015	tote	
553	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 31, 2015	pot	
554	WA	Pacific Beach	47.208714	-124.210833	Apr 12. 2015	plastic object	
555*	HI	Oahu: Alan Davis Beach	21.297578	-157.654742	Apr 22, 2015	vessel	Miyagi
556	OR	Bandon: Mars Street	43.087114	-124.436469	Jan 14, 2016	bucket lid	
557	OR	Gold Beach: Crook Point	42.25125	-124.412772	Mar 26, 2016	tote	
558	OR	Gold Beach: Crook Point	42.25125	-124.412772	Mar 26, 2016	tote	
559	OR	Gold Beach: Crook Point	42.25125	-124.412772	Mar 26, 2016	buoy	
560	OR	Gold Beach: Crook Point	42.25125	-124.412772	Mar 26, 2016	black bar	
561	OR	Bandon	43.115111	-124.436436	Nov 6, 2015	tote	
562	OR	Gold Beach: Pistol River	42.277378	-124.408819	Mar 18, 2016	buoy/rope	
563	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 2, 2015	tote	
564	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 2, 2015	lid	
565	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 2, 2015	tote	
566	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	lid	
567	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 25, 2015	buoy	
569	OR	Manzanita	45.720494	-123.945572	Feb 28, 2015	bowl	
570	OR	Manzanita	45.720494	-123.945572	Feb 28, 2015	tote	
571	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	tote	
572	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	bumper	
573	OR	in ocean off Heceta Head	44.1355 **	-124.220289 **	Dec2014-March 2015	tote	
574	OR	in ocean off Heceta Head	44.1355 **	-124.220289 **	Feb 10, 2015	tote	
575	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	tote	
576	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	jug	
577	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	tote	
578	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	tote	
579	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	float	
580	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	tote	
581	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	bowl	
582	WA	Long Beach Peninsula	46.475511	-124.071969	Dec2014-March 2015	lid	
583	WA	Long Beach Peninsula	46.475511	-124.071969	Dec2014-March 2015	plastic fragment	
585	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	cylinder	
586	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 2014-March 2015	shelving	
587	WA	Long Beach Peninsula	46.475511	-124.071969	Dec2014-March 2015	tote	
588	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 25, 2015	lid	
589	OR	Moolack / Beverly Beach	44.715225	-124.060472	Jun 15, 2016	buoy	
590	OR	Crook Point	42.25125	-124.412772	Mar 16, 2016	buoy	
591	WA	Olympic National Park: Mosquito Creek	47.798108	-124.482242	Apr 21, 2015	tote	
592	OR	Bandon: Mars Street	43.087114	-124.436469	Jan 14, 2016	tote	
593	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 16, 2016	tote	
594	WA	Long Beach Peninsula: Leadbetter	46.475511	-124.071969	Feb 1, 2016	tote	
595	WA	Long Beach Peninsula: Leadbetter	46.475511	-124.071969	Feb 1, 2016	tote	
596	OR	Lane County: Bob Creek Wayside	44.262031	-124.110000	Apr 19, 2015	tote	
597	WA	North Ocean Park	46.475511	-124.071969	Jan 24, 2016	tote	
598	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 16, 2016	buoy	
599	WA	Long Beach Peninsula	46.475511	-124.071969	Apr 26, 2015	tote	
600	OR	Crook Point South	42.25125	-124.412772	Jun 15, 2016	bottle cap	
601	OR	Crook Point South	42.25125	-124.412772	Jun 15, 2016	buoy	
602	OR	Crook Point South	42.25125	-124.412772	Jun 17, 2016	tire	
603	WA	Beard's Hollow, south of Long Beach	46.305194	-124.075278	May 16, 2015	tote	
604	WA	Long Beach Peninsula	46.475511	-124.071969	May 2016	tote	
605	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	2015	buoy	
606	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 8, 2015	buoy	
607	WA	Surfside	46.475511	-124.071969	May 17, 2015	buoy	
608	WA	Long Beach Peninsula: near Ocean Park	46.475511	-124.071969	Apr 15, 2015	tote	
609	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 15, 2016	buoy	
610	WA	Long Beach Peninsula: Leadbetter	46.475511	-124.071969	May 14, 2015	tote	

* = JTMD-HR: JTMD objects most thoroughly sampled (Higher Resolution) for macrobiota diversity.
OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-1. Japanese Tsunami Marine Debris Register (from Carlton et al., 2017) (cont'd)

JTMD-BF-#	State or Province	Location	Latitude (**=estimate)	Longitude (**=estimate)	Date	Object	Prefecture (and city) origin in Japan
611	WA	3 miles north of Long Beach	46.475511	-124.071969	May 13, 2015	buoy	
612	WA	Long Beach Peninsula: Leadbetter	46.475511	-124.071969	Mar 16, 2016	buoy	
613	WA	Long Beach Peninsula: Leadbetter	46.475511	-124.071969	Feb 19, 2016	buoy	
614	OR	Lincoln County: Moolack Beach	44.699717	-124.0636	Apr 11, 2016	tote	
615	WA	Long Beach Pen.: 4.8 km south of Leadbetter Pt.	46.475511	-124.071969	May 26, 2015	buoy	
616	WA	Long Beach Peninsula	46.475511	-124.071969	May-Sep 2015	can	
617	WA	Quinault Indian Reservation: South Queets	47.400867	-124.330544	May 21, 2015	fiberglass foam piece	
618	WA	Long Beach Peninsula	46.475511	-124.071969	Jan 12, 2016	buoy	
619	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Dec 24, 2015	buoy	
621	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Dec 22, 2015	buoy/rope	
622	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Dec 25, 2015	tote	
623	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Dec. 24, 2015	tote	
624	OR	0.5 miles north of Yaquina Head light, Newport	44.679414	-124.070833	Dec 20, 2015	tote	
625	WA	Long Beach Peninsula	46.475511	-124.071969	Jun 2, 2015	pallet	
626	HI	Kauai: Kapa'a	22.081806	-159.312128	Jun 25, 2016	vessel	Miyagi
627	HI	Kauai: Kapa'a Beach	22.081806	-159.312128	Apr 1, 2016 [re-drift]	post-and-beam wood	
628	OR	Newport: South Beach	44.607683	-124.0687	Apr 24, 2013	post-and-beam wood	
629	OR	Newport: South Beach	44.607683	-124.0687	Apr 27, 2013	post-and-beam wood	
630	OR	Newport: South Beach	44.607683	-124.0687	Apr 27, 2013	post-and-beam wood	
631	WA	Grays Harbor County: Roosevelt Beach	47.175278	-124.199167	Aug 12, 2015	pallet	
632	OR	Seal Rock: Quail Street	44.483056	-124.083808	Apr 14, 2015	tote	
633	HI	Kauai: Waipake Beach	22.207492	-159.338625	Sep 29, 2013	post-and-beam wood	
634	OR	Newport: South Beach	44.607683	-124.0687	Mar 16, 2016	buoy	
635	OR	Moolack Beach	44.699717	-124.0636	May 17, 2016	buoy	
636	OR	Manzanita	45.720494	-123.945572	Feb 28, 2015	tote	
637	OR	Moolack Beach	44.699717	-124.0636	Apr 8, 2015	tote	
638	OR	Sacchi Beach	43.264578	-124.38645	Apr 23, 2016	vessel	Miyagi
639	WA	Long Beach Peninsula	46.475511	-124.071969	Feb-May 2016	buoy	
640	OR	Newport: Agate Beach	44.66455	-124.061158	Mar 23, 2016	tote	
641	WA	Long Beach Peninsula	46.475511	-124.071969	Jul 5, 2016	pallet	
642	WA	Long Beach Peninsula	46.475511	-124.071969	Jul 6, 2016	tote	
643	WA	Long Beach Peninsula	46.475511	-124.071969	Mar 15, 2016	buoy	
645	WA	Long Beach Peninsula	46.475511	-124.071969	Jan-May 2016	buoy	
646	OR	Manzanita	45.720494	-123.945572	Feb 28, 2015	bucket	
647	WA	Long Beach Peninsula: Leadbetter Point	46.475511	-124.071969	Mar 15, 2016	buoy	
648	OR	Crook Point South	42.25125	-124.412772	Mar 26, 2016	lid	
649	OR	Moolack / Beverly Beach	44.715225	-124.060472	Apr 10, 2016	jug	
650	WA	Long Beach Peninsula	46.475511	-124.071969	Jul 10, 2016	table	
651	OR	Nye Beach	44.642333	-124.063011	Jul 13, 2016	tree	
652*	OR	Falcon Cove	45.781247	-123.969906	Jul 20, 2016	vessel	
653	HI	Oahu: Kahuku	21.683367	-157.944247	Mar 13, 2016	buoy	
654	HI	Oahu: Kailua	21.405117	-157.738383	Mar 11, 2016	buoy	
655	HI	Papahanaumokuake Marine Nat'l Monument, in ocean	25.752922 **	-170.458333 **	Jun 1, 2015	fish bin	
656	OR	Otter Crest	44.756714	-124.064444	Mar 26, 2016	jug	
657	WA	Long Beach Peninsula	46.475511	-124.071969	April-May 2015	buoy	
658	OR	Newport: South Beach	44.607683	-124.0687	Oct 5, 2016	pallet	
659	WA	Long Beach Peninsula	46.475511	-124.071969	May 2015	tote	
660	WA	Long Beach Peninsula	46.475511	-124.071969	2014	tire	
661	HI	Hawaii: south of Honokohau Harbor, Kona	19.664656	-156.030736	Nov 17, 2016	buoy	
662	HI	Hawaii: Kamilo Point	18.974297	-155.597222	Nov 19, 2016	tote	
663	WA	Long Beach Peninsula	46.475511	-124.071969	Nov 8, 2016	tote	
664	WA	Long Beach Peninsula	46.475511	-124.071969	Nov 30, 2016	buoy	
665	WA	Long Beach Peninsula	46.475511	-124.071969	Dec 1, 2016	buoy	
666	CA	Daly City: Mussel Rock Beach	37.672642	-122.495833	Jul 25, 2015	tote	
667*	HI	Kauai: Kapa'a	22.081806	-159.312128	Dec 7, 2016	rope/buoys	
668	OR	Bandon	43.088001	-124.435364	Mar 15, 2016	tube	
669	OR	Bandon	43.088001	-124.435364	Mar 15, 2016	sieve	
670	OR	Bandon	43.088001	-124.435364	Mar 15, 2016	pot	
671	OR	Bandon	43.088001	-124.435364	Mar 15, 2016	tubing	
672	OR	Bandon	43.088001	-124.435364	Apr 18, 2016	lid	
673	WA	Long Beach Peninsula	46.475511	-124.071969	May 27-Sep 15, 2015	tote	
674	WA	Long Beach Peninsula	46.475511	-124.071969	May 27-Sep 15, 2015	plastic piece	
675	HI	Oahu: Waimanalo	21.328933	-157.689167	Dec 22, 2016	vessel	Miyagi
676	OR	Bandon	43.088001	-124.435364	Dec 15, 2016	tote	
677	HI	Hawaii: southeast coast on DHHL lands	18.911128	-155.678056	Jan 16, 2017	vessel	
678	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 12, 2017	buoy	
679*	WA	Long Beach Peninsula	46.475511	-124.071969	Feb 16, 2017	buoy	

* = JTMD-HR: JTMD objects most thoroughly sampled (Higher Resolution) for macrobiota diversity.
OR = Oregon, WA = Washington, CA = California, HI = Hawaii, BC = British Columbia

Appendix 7-2. Scientists contributing to the JTMD taxonomic effort (from Carlton et al., 2017)

Scientist	Affiliation	Taxon
Bjørn Altermark	Arctic University of Norway, Tromsø, Norway	Teredinidae
Claudia Arango	Queensland Museum, Australia	Pycnogonida
David Bilderback	Bandon, Oregon, USA	Bryozoa
Philip E. Bock	Mount Waverley, Victoria, Australia	Bryozoa
Luisa M. S. Borges	Helmholtz-Zentrum Geesthacht, Germany	Teredinidae
Ralph Breitenstein	Oregon State University, Hatfield Marine Science Center, USA	General invertebrates
Stephen Cairns	Smithsonian Institution, National Museum of Natural History, USA	Scleractinia
Dale Calder	Royal Ontario Museum, Canada	Hydrozoa
James T. Carlton	Williams College, Massachusetts USA and Williams-Mystic Maritime Studies Program, Connecticut, USA	General invertebrates; Mollusca; Cirripedia
Benny Chan	Academia Sinica, Taiwan, Chinese Taipei	Cirripedia
John W. Chapman	Oregon State University, Hatfield Marine Science Center, USA	Amphipoda, Isopoda, Tanaidacea, Decapoda; general invertebrates
Henry Choong	Royal British Columbia Museum, Canada	Hydrozoa
Eugene V. Coan	Santa Barbara Museum of Natural History, California, USA	Bivalvia
Jeffery R. Cordell	University of Washington, USA	Copepoda
Matthew T. Craig	NOAA, National Marine Fisheries Service, La Jolla, California, USA	Pisces
Natalia Demchenko	Zhirmunsky Institute, Vladivostok, Russia	Amphipoda
Matthew Dick	Hokkaido University, Japan	Bryozoa
Anthony Draeger	Kensington, California, USA	Polyplacophora
Douglas J. Eernisse	California State University, Fullerton, USA	Gastropoda; Polyplacophora
David Elvin	Oregon Marine Porifera Project, Shelburne, Vermont, USA	Porifera
Neal Evenhuis	B. P. Bishop Museum, Hawaii, USA	Chironomidae
Daphne Fautin	University of Kansas, USA	Anthozoa
Karin H. Fehlauer-Ale	Universidade Federal do Paraná, Brazil	Bryozoa
Kenneth Finger	University of California, Berkeley, USA	Foraminifera
Megan Flenniken	Stony Brook University, New York, USA	Anthozoa
Toshio Furota	Toho University, Japan	General invertebrates
Aaron Gann	Oregon State University, USA	Pisces
Jonathan Geller	Moss Landing Marine Laboratories, USA	General invertebrates
Jeffrey H. R. Goddard	University of California, Santa Cruz, USA	Nudibranchia
Scott Godwin	NOAA Honolulu, USA	General invertebrates
Dennis P. Gordon	National Institute of Water and Atmospheric Research, Wellington, New Zealand	Bryozoa
Terry Gosliner	California Academy of Sciences, San Francisco, USA	Nudibranchia
Takuma Haga	National Museum of Nature and Science, Tokyo, Japan	Bivalvia
Niels-Viggo Hobbs	University of Rhode Island, USA	Isopoda
Leslie Harris	Los Angeles County Museum of Natural History, USA	Polychaeta
John Holleman	Merritt College, Oakland, California, USA	Platyhelminthes
Gyo Itani	Kochi University, Japan	Decapoda
Collin Johnson	Harvard University, USA	Bryozoa
Hiroshi Kajihara	Hokkaido University, Japan	Nemertea

Appendix 7-2. Scientists contributing to the JTMD taxonomic effort (from Carlton et al., 2017) (cont'd)

Scientist	Affiliation	Taxon
Gerald Krantz	Oregon State University, USA	Halacaridae
Elena Kupriyanova	Australian Museum, Australia	Serpulidae
Gretchen Lambert	University of Washington, USA	Ascidiacea
Robert N. Lea	California Academy of Sciences, San Francisco, California, USA (formerly California Department of Fish and Wildlife)	Pisces
Katrina Lohan	Smithsonian Environmental Research Center, Edgewater, Maryland, USA	Haplosporida
Konstantin Lutaenko	Zhirmunsky Institute, Vladivostok, Russia	Mytilidae
Joshua Mackie	California State University, San Jose, USA	Bryozoa
Christopher Mah	Smithsonian Institution, National Museum of Natural History, USA	Asteroidea
Svetlana Maslakova	University of Oregon Institute of Marine Biology, USA	Nemertea
Linda McCann	Smithsonian Environmental Research Center, Edgewater, Maryland, USA	Bryozoa
Megan I. McCuller	Williams College, Massachusetts, USA and Williams-Mystic Maritime Studies Program, Connecticut, USA	Bryozoa
Mary McGann	U.S. Geological Survey, Menlo Park, California, USA	Foraminifera
Gary McDonald	University of California, Santa Cruz, USA	Nudibranchia
James H. McLean	Los Angeles County Museum of Natural History, USA	Gastropoda
Richard Mooi	California Academy of Sciences, San Francisco, California, USA	Echinoidea
Bruce Mundy	National Marine Fisheries Service, Hawaii, USA	Pisces
Katherine Newcomer	Smithsonian Environmental Research Center, Edgewater, Maryland, USA	Anthozoa
Eijiroh Nishi	Yokohama National University, Japan	Annelida
Teruaki Nishikawa	Nagoya University, Japan	Sipuncula
Atsushi Nishimoto	National Research Institute of Fisheries Sciences, Japan	Teredinidae
Jerrold G. Norton	Pacific Grove, California, USA (formerly National Marine Fisheries Service)	Pisces
Ronald Noseworthy	Jeju National University, Korea	Polyplacophora
Peter Ng	National University of Singapore, Singapore	Decapoda
Michio Otani	Osaka Museum of Natural History, Japan	Cirripedia; General invertebrates
David Pawson	Smithsonian Institution, National Museum of Natural History, USA	Holothuroidea
Erik Pilgrim	National Exposure Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA	Gastropoda, Polyplacophora
Michael J. Raupach	Carl von Ossietzky University, Oldenburg, Germany	Teredinidae
Gregory Ruiz	Smithsonian Environmental Research Center, Edgewater, Maryland, USA	Haplosporida, Hydrozoa
Hiroshi Saito	National Museum of Nature and Science, Japan	Polyplacophora
Eric Sanford	University of California, Davis, Bodega Marine Laboratory, California USA	Anthozoa
J. Reuben Shipway	Northeastern University, Nahant, Massachusetts USA	Teredinidae
Ashleigh Smythe	Virginia Military Institute, USA	Nematoda
Jackie Sones	University of California, Davis, Bodega Marine Laboratory, California, USA	Anthozoa
Ichiro Takeuchi	Ehime University, Japan	Amphipoda
Hayato Tanaka	The University of Tokyo, Japan	Ostracoda
Paul D. Taylor	Natural History Museum, London, England	Bryozoa
Nancy Treneman	University of Oregon Institute of Marine Biology, USA	Teredinidae
Paul Valentich-Scott	Santa Barbara Museum of Natural History, California, USA	Bivalvia
Leandro Manzoni Vieira	Universidade Federal de Pernambuco, Brazil	Bryozoa
Judith Winston	Smithsonian Marine Station, Fort Pierce, Florida, USA	Bryozoa
Moriaki Yasuhara	University of Hong Kong, China	Ostracoda

Appendix 7-3. JTMD-Biodiversity: Master species list (from Carlton et al., 2017)

Japanese species

- **CHROMISTA**
  - **RHIZARIA**
    - **FORAMINIFERA**
      - *Acervulina inhaerens*
      - *Bolivina* cf. *B. seminude*
      - *Cibicides lobatulus*
      - *Dyocibicides perforate*
      - *Elphidium crispum*
      - *Nonionella stella*
      - *Planogypsina squamiformis*
      - *Planorbulina mediterranensis*
      - *Rosalina globularis**
      - *Cornuspira involvens**
      - *Miliolinella subrotunda**
      - *Trochammina* sp.
      - *Homotrema rubra*
    - **CERCOZOA**
      - *Gromia "oviformis"*
  - **ALVEOLATA**
    - **CILIOPHORA**
      - **Suctoria**
        - Species A (yellow)
        - Species B (white)
      - **Heterotrichea**
        - **Folliculinidae**
          - Unidentified sp.
      - **Sessilida**
        - **Vorticellidae**
          - *Vorticella* sp.
        - **Zoothamniidae**
          - *Zoothamnium* sp.
- **ANIMALIA**
  - **PORIFERA**
    - *Callyspongia* sp.*
    - *Chalinidae*, unidentified sp.
    - *Clathrina* sp.*
    - *Cliona* sp.
    - *Halichondria panacea**
    - *Hymeniacidon sinapium**
    - *Leucandra* sp.*
    - *Leucosolenia eleanor**
    - *Mycale macginitei**
    - *Sycon raphanus**
    - *Ute* sp.*
- **CNIDARIA**
  - **Hydrozoa**
    - **Thecata**
      - *Abietinaria inconstans*
      - *Aglaophenia* aff. *A. pluma*
      - *Amphisbetia furcate**
      - *Antenella* sp.
      - *Campanularia volubilis**
      - *Clytia hemisphaerica**
      - *Clytia linearis*
      - *Clytia* cf. *C. universitatis*
      - *Eutima japonica*
      - *Halecium tenellum*
      - *Halecium delicatulum*
      - *Halopteris* aff. *Campanula**
      - *Hydrodendron gracile*
      - *Hydrodendron mirabile*
      - *Laomedea flexuosa**
      - *Obelia longissimi**
      - *Obelia dichotoma*
      - *Obelia geniculate**
      - *Orthopyxis caliculata*
      - *Orthopyxis platycarpa*
      - *Phialella quadrata*
      - *Plumalecium plumularioides**
      - *Plumularia setacea* *
      - *Plumularia caliculata*
      - *Sertularella* sp. A
      - *Sertularella mutsuensis*
      - *Symplectoscyphus tricuspidatus*
    - **Anthoathecata**
      - *Stylacteria* sp.
      - *Bougainvillia muscus?*
      - Unidentified sp. A
  - **Anthozoa**
    - **Actiniaria**
      - *Metridium dianthus*
      - *Anthopleura sp.**
      - *Diadumene lineata**
      - *Urticina* sp.?
      - *Actiniaria* sp. A
      - *Actiniaria* sp. B
      - *Actiniaria* sp. C
    - **Scleractinia**
      - *Pocillopora damicornis*
- **NEMATODA**
  - Unidentified spp. (3+)
- **NEMERTEA**
  - *Lineidae*, unidentified sp.
  - *Quasitetrastemma nigrifrons*
  - *Oerstedia dorsalis*
  - Unidentified sp.
- **PLATYHELMINTHES**
  - **RHABDITOPHORA**
    - **Tricladida**
      - **Uteriporidae?**
        - Unidentified spp. (2+)
    - **Monogenea**
      - *Benedenia seriolae?*
      - *Heteraxine heterocerca?*
- **SIPUNCULA**
  - *Phascolosoma scolops*
- **ANNELIDA**
  - **Oligochaeta**
    - Unidentified spp. (2+)
  - **Polychaeta**
    - **Capitellidae**
      - Unidentified sp.
    - **Nereididae**
      - *Nereis pelagica*
      - *Perinereis nigropunctata*
    - **Phyllodocidae**
      - *Eulalia quadrioculata*
      - *Eulalia viridis*-complex
      - *Eteone* sp.
      - *Nereiphylla* cf. *N. castanea*
    - **Polynoidae**
      - *Halosydna brevisetosa*-complex
      - *Harmothoe imbricata*
      - *Lepidonotus* sp.
    - **Syllidae**
      - *Syllis elongata*-complex
      - *Syllis hyalina*-complex
      - *Syllis* cf. *S. ehlersoides*
      - *Syllis* cf. *S. farallonensis*
      - *Syllis* cf. *S. pulchra*
      - *Syllis gracilis*-complex
      - *Syllinae* spp. 1-6
      - *Sphaerosyllis* sp.
      - *Trypanosyllis zebra?*
      - *Amblosyllis speciosa*-complex (D)
    - **Terebellidae**
      - *Amphitrite* sp.
      - *Terebella* sp.
    - **Oenonidae**
      - *Arabella semimaculata*-group
    - **Onuphidae**
      - Unidentified sp.
    - **Spionidae**
      - *Polydora* sp.
      - *Pygospio californica*
    - **Orbiniidae**
      - *Naineris* sp.
    - **Chrysopetalidae**
      - Unidentified sp.
      - *Paleanotus* sp.
    - **Acrocirridae**
      - *Acrocirrus* sp.
    - **Fabriciidae**
      - Unidentified sp.
    - **Sabellariidae?**
      - Unidentified sp.
    - **Sabellidae**
      - *Amphiglena* sp.
    - **Serpulidae**
      - *Hydroides ezoensis*
      - *Serpula* sp.
      - *Spirobranchus* cf. *S. minutus*
      - *Spirobranchus* sp.
      - *Salmacina* sp.?
    - **Spirorbidae**
      - Unidentified spp.
- **MOLLUSCA**
  - **Gastropoda**
    - **Lottiidae**
      - *Lottia dorsuosa*
      - *Lottia versicolor*
      - *Lottia tenuisculpta*
      - *Lottia kogamogai*
      - *Lottia* sp.
      - *Lottia* sp. N-D Eernisse
      - *Lottia* sp. O
      - *Lottia* sp. BF3
      - *Nipponacmea habei*
    - **Nacellidae**
      - *Cellana grata*
    - **Calyptraeidae**
      - *Crepidula onyx*
    - **Vermetidae**
      - *Serpulorbis* sp.
    - **Columbellidae**
      - *Mitrella moleculina*
      - *Mitrella* sp. A
    - **Muricidae**
      - *Reishia bronni*
  - **Pulmonata**
    - **Siphonariidae**
      - *Siphonaria sirius*
      - *Siphonaria* sp.
  - **Aplysiida**
    - *Dolabella auricularia*
  - **Nudibranchia**
    - *Hermissenda crassicornis*
    - *Dendronotus frondosus*
    - *Eubranchus* sp.
    - *Dorididae*, unidentified sp.
    - Unidentified sp.
  - **Bivalvia**
    - **Mytilidae**
      - *Mytilus galloprovincialis**
      - *Mytilus coruscus*
      - *Mytilus trossulus*
      - *Modiolus kurilensis*
      - *Modiolus nipponicus*
      - *Modiolarca cuprea*
      - *Trichomusculus semigranatus*
      - *Mytilisepta virgata*
      - *Septifer bilocularis*
      - *Lithophaga lischkei*
    - **Anomiidae**
      - *Monia umbonata*
      - *Monia macrochisma*
    - **Gryphaeidae**
      - *Hyotissa quercinus*
      - *Neopycnodonte cochlear*

Appendix 7-3. JTMD-Biodiversity: Master species list (from Carlton et al., 2017) (cont'd)

Japanese species

- **Ostreidae**
  - *Crassostrea gigas*
  - *Crassostrea bilineata*
  - *Crassostrea circumpicta*
  - *Dendostrea folium*
- **Spondylidae**
  - *Spondylus cruentus*
- **Arcidae**
  - *Arca boucardi*
  - *Hawaiarca uwaensis*
  - *Barbatia lima*
  - *Barbatia virescens*
- **Pectinidae**
  - *Glorichlamys quadrilirata*
  - *Laevichlamys squamosa*
  - *Laevichlamys cuneata*
  - *Pascahinnites coruscans*
  - *Patinopecten yessoensis*
  - *Semipallium barnetti*
- **Limidae**
  - *Limaria hirasei*
- **Pteriidae**
  - *Pteria* sp.
  - *Pinctada albina*
  - *Pinctada margaritifera*
  - *Isognomon legumen*
- **Malleidae**
  - *Malleus irregularis*
- **Chamidae**
  - *Chama argentata*
  - *Chama cerinorhodon*
  - *Chama dunkeri*
  - *Chama japonica*
- **Myidae**
  - *Sphenia coreanica*
- **Hiatellidae**
  - *Hiatella orientalis*
- **Teredinidae**
  - *Psiloteredo* sp.*
  - *Teredothyra smithi**
  - *Bankia carinata*
  - *Bankia bipennata*
  - *Lyrodus takanoshimensis*
  - *Teredo navalis*
- **Polyplacophora**
  - *Mopalia seta*
  - *Acanthochitona achates*
  - *Acanthochitona* sp. A
  - *Acanthochitona rubrolineata*
  - *Placiphorella stimpsoni*
- **ARTHROPODA**
  - **CRUSTACEA**
    - **Copepoda**
      - *Harpacticus* sp.- *flexus* group
      - *Harpacticus compsonyx**
      - *Harpacticus septentrionalis**
      - *Harpacticus nicaceensis**
      - *Harpacticus* sp.*
      - *Parastenhelia spinose**
      - *Tisbe* spp.*
      - *Paralaophonte congenera**
      - *Sarsamphiascus minutus**
      - *Sarsamphiascus varians* group*
      - *Heterolaophonte discophora**
      - *Heterolaphonte* sp.
      - *Paramphiascella fulvofasciata**
      - *Ambunguipes* aff. *rufocincta*
      - *Dactylopodamphiascopsis latifolius**
    - **Ostracoda**
      - *Sclerochilus verecundus*
      - *Sclerochilus* sp. 1
      - *Sclerochilus* sp. 2
      - *Xestoleberis setouchiensis**
      - *Obesotoma* cf. *O. setosum*
      - *Obesotoma* sp.
      - *Paradoxostomatidae* unidentified sp.
    - **Cirripedia**
      - *Megabalanus rosa*
      - *Megabalanus zebra*
      - *Megabalanus* sp.
      - *Semibalanus cariosus**
      - *Balanus crenatus*
      - *Balanus glandula*
      - *Balanus trigonus*
      - *Chthamalus challengeri*
      - *Pseudoctomeris sulcata*
      - *Tetraclita japonica*
    - **Amphipoda**
      - **Ischyroceridae**
        - *Jassa marmorata*-complex*
      - **Ampithoidae**
        - *Ampithoe valida*
        - *Ampithoe lacertosa*
        - *Ampithoe koreana*
      - **Stenothoidae**
        - *Stenothoe crenulata*-complex
      - **Photidae**
        - *Gammaropsis japonica*
      - **Dogielinotidae**
        - *Allorchestes* sp.
      - **Pleustidae**
        - *Trachypleustes* sp.
      - **Caprellidae**
        - *Caprella mutica**
        - *Caprella cristibrachium**
        - *Caprella penantis*
        - *Caprella equilibra*
        - *Caprella drepanochir*
    - **Tanaidacea**
      - *Zeuxo normani**
    - **Isopoda**
      - *Ianiropsis serricaudis**
      - *Ianiropsis derjugini*
      - *Munna japonica*
      - *Dynoides spinipodus*
    - **Decapoda**
      - *Hemigrapsus sanguineus*
      - *Oedignathus inermis*
      - *Sphaerozius nitidus*
  - **Pycnogonida**
    - *Endeis nodosa*
  - **Insecta**
    - **Diptera**
      - *Telmatogeton japonicas**
  - **Acarina**
    - **Halacaridae**
      - *Halacarellus schefferi*
- **BRYOZOA**
  - **Cheilostomata**
    - *Aetea anguina*
    - *Callaetea* sp.
    - *Biflustra grandicella*
    - *Biflustra irregulata*
    - *Biflustra* cf. *B. arborescens*
    - *Arbocuspis* sp.
    - *Bugula* sp.*
    - *Bugulina stolonifera*
    - *Callopora craticula*
    - *Catenicella* sp.
    - *Cauloramphus spinifer*
    - *Cauloramphus* sp. A
    - *Celleporaria brunnea*
    - *Celleporella hyalina**
    - *Celleporina porosissima*
    - *Celleporina* cf. *C. globosa*
    - *Celleporina* sp. A
    - *Celleporina* sp. B
    - *Conopeum nakanosum*
    - *Cribrilina mutabilis*
    - *Cryptosula pallasiana*
    - *Drepanophora* cf. *D. gutta*
    - *Escharella hozawai**
    - *Exochella tricuspis**
    - *Fenestrulina* cf. *F. orientalis**
    - *Membranipora villosa*
    - *Metroperiella* cf. *M. biformis**
    - *Microporella borealis*
    - *Microporella luellae*
    - *Microporella neocribroides*
    - *Rhynchozoon* sp.
    - *Schizoporella japonica*
    - *Scruparia ambigua**
    - *Smittoidea spinigera*
    - *Tricellaria inopinata**
    - *Watersipora mawatarii*
    - *Watersipora* cf. *W. typica*
  - **Cyclostomata**
    - *Crisia* sp. A*
    - *Crisia* cf. *C. serrulata*
    - *Crisidia* sp.
    - *Disporella* cf. *D. novaehollandiae*
    - *Entalophora* sp.?
    - *Filicrisia* cf. *F. franciscana*
    - *Proboscina* sp.
    - *Stomatopora* sp.
    - *Tubulipora misakiensis*
    - *Tubulipora pulchra*
  - **Ctenostomata**
    - *Alcyonidium* sp.
    - *Walkeria prorepens*
- **KAMPTOZOA**
  - *Barentsia* sp.
- **ECHINODERMATA**
  - **Asteroidea**
    - *Asterias amurensis*
    - *Aphelasterias japonica*
    - *Patiria pectinifera*
  - **Echinoidea**
    - *Temnotrema sculptum*
  - **Holothuroidea**
    - *Havelockia versicolor*
  - **Ophiuroidea**
    - Unidentified sp.
- **CHORDATA**
  - **Ascidiacea**
    - *Botrylloides* sp.
    - *Botryllus* sp.
    - *Didemnum perlucidum*
    - *Didemnum vexillum*
    - *Herdmania* cf. *H. pallida*
    - *Perophora* sp.
  - **Pisces**
    - *Oplegnathus fasciatus*
    - *Seriola aureovittata*

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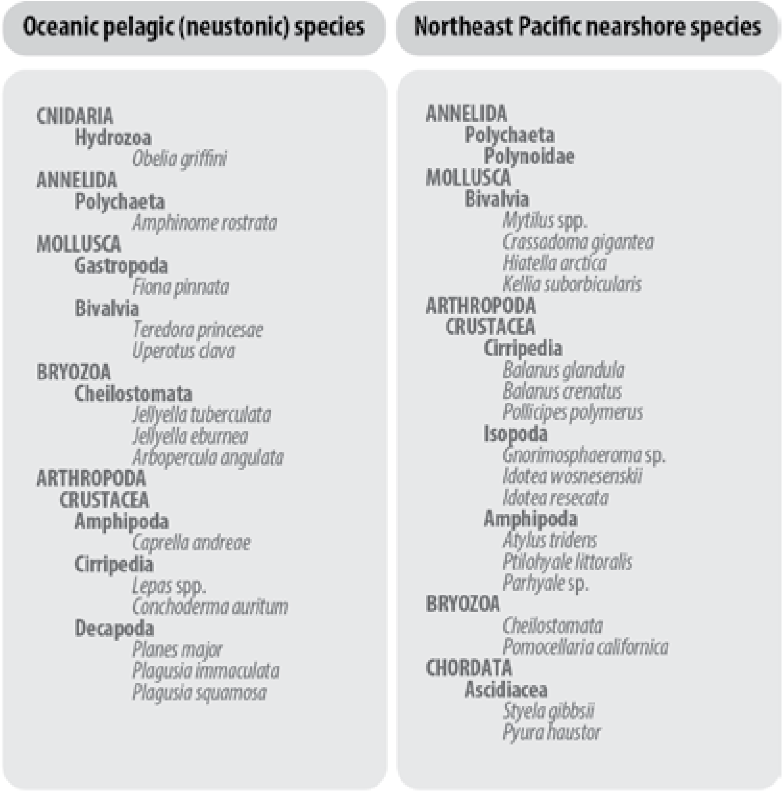
* Asterisked species were reproductive upon arrival (with gametes, gametic tissue, or brooded young) or were present in two or more age classes (generations).

Appendix 7-3. JTMD-Biodiversity: Master species list (from Carlton et al., 2017) (cont'd)



Oceanic pelagic (neustonic) species

- **CNIDARIA**
  - **Hydrozoa**
    - *Obelia griffini*
- **ANNELIDA**
  - **Polychaeta**
    - *Amphinome rostrata*
- **MOLLUSCA**
  - **Gastropoda**
    - *Fiona pinnata*
  - **Bivalvia**
    - *Teredora princesae*
    - *Uperotus clava*
- **BRYOZOA**
  - **Cheilostomata**
    - *Jellyella tuberculata*
    - *Jellyella eburnea*
    - *Arbopercula angulata*
- **ARTHROPODA**
  - **CRUSTACEA**
    - **Amphipoda**
      - *Caprella andreae*
    - **Cirripedia**
      - *Lepas* spp.
      - *Conchoderma auritum*
    - **Decapoda**
      - *Planes major*
      - *Plagusia immaculata*
      - *Plagusia squamosa*

Northeast Pacific nearshore species

- **ANNELIDA**
  - **Polychaeta**
    - **Polynoidae**
- **MOLLUSCA**
  - **Bivalvia**
    - *Mytilus* spp.
    - *Crassadoma gigantea*
    - *Hiatella arctica*
    - *Kellia suborbicularis*
- **ARTHROPODA**
  - **CRUSTACEA**
    - **Cirripedia**
      - *Balanus glandula*
      - *Balanus crenatus*
      - *Pollicipes polymerus*
    - **Isopoda**
      - *Gnorimosphaeroma* sp.
      - *Idotea wosnesenskii*
      - *Idotea resecata*
    - **Amphipoda**
      - *Atylus tridens*
      - *Ptilohyale littoralis*
      - *Parhyale* sp.
- **BRYOZOA**
  - *Cheilostomata*
  - *Pomocellaria californica*
- **CHORDATA**
  - **Ascidiacea**
    - *Styela gibbsii*
    - *Pyura haustor*

Appendix 7-4. Species on JTMD derived from southern Asian waters (species occurring south of the Boso Peninsula, Japan)

Taxon	Species	Range	First appearance	
			Hawaiian Islands	North America
CNIDARIA: Anthozoa (sea anemones, corals)	*Anthopleura* sp.	Southern Japan and south		2016
	Pocillopora damicornis	Southern Japan and south; subtropical and tropical		2015
ANNELIDA: Polychaeta (worms)	*Salmacina* sp.	Southern Japan and south		2016
CRUSTACEA: Cirripedia (barnacles)	*Pseudoctomeris sulcata*	south of Boso Peninsula		2012
CRUSTACEA: Amphipoda (amphipods)	*Trachypleustes* sp.	Subtropical–tropical	2016	
CRUSTACEA: Brachyura (crabs)	*Sphaerozius nitidus*	Indo–West Pacific		2016
MOLLUSCA: Gastropoda (snails)	*Mitrella moleculina*	Boso Peninsula and south		2012
MOLLUSCA: Bivalvia (oysters, mussels, clams, scallops, shipworms, etc.)	*Trichomusculus semigranatus*	Boso Peninsula and south		2014
	Septifer bilocularis	Boso Peninsula and south		2015
	Crassostrea bilineata	Okinawa Island and south		2016
	Dendostrea folium	Kii Peninsula and south	2016	2014
	Chama argentata	Boso Peninsula and south		2015
	Chama dunkeri	Boso Peninsula and south		2015
	Hyotissa quercinus	Sagami Bay and south	2013	2013
	Neopycnodonte cochlear	warm temperate– subtropical	2016	2014
	Laevichlamys squamosa	Kii Peninsula and south	2015	2015
	Laevichlamys cuneata	southern Japan and south		2014
	Pascahinnites coruscans	Kii Peninsula and south		2015
	Glorichlamys quadrilirata	southern Japan and south		2015
	Semipallium barnetti	southern Japan and south		2015
	Sphenia coreanica	Boso Peninsula and south	2013	2015
	Hawaiarca uwaensis	Boso Peninsula and south		2015
	Spondylus cruentus	Boso Peninsula to Okinawa		2014
	Limaria hirasei	Boso Peninsula and south		2015
	Pteria sp.	Boso–Kii Peninsulas and south	2013 (Midway)	
	Pinctada albina	Amami Islands and south		2014
	Pinctada margaritifera	Kii Peninsula and south	2015	
	Isognomon legumen	Boso Peninsula and south	2016	2015
	Malleus irregularis	Boso Peninsula and south		2015
	Bankia carinata	warm temperate–subtropical		2013
	Bankia bipennata	warm temperate–subtropical		2013
	Teredothyra smithi	warm temperate–subtropical	2013	2013

Appendix 7-4. Species on JTMD derived from southern Asian waters (species occurring south of the Boso Peninsula, Japan) (cont'd)

Taxon	**Species**	**Range**	**First appearance**	
			Hawaiian Islands	**North America**
BRYOZOA (bryozoans)	*Biflustra grandicella*	South China Sea and south		2013
	Biflustra irregulata	South China Sea, South Korea, and south		2013
	Celleporaria brunnea	South Korea (but may have extended north into Japan as a range expansion; McCuller et al., 2018, p. 141).	2013	2014
	Celleporina sp. cf. *globosa*	China		2013
	Drepanophora sp. cf. *gutta*	tropical		2015
	Metroperiella sp. cf. *biformis*	East China Sea and south		2014
	Smittoidea spinigera	warm temperate– subtropical	2013	2014
ASCIDIACEA (sea squirts)	*Herdmania* sp. cf. *pallida*	subtropical, tropical		2016

Japan NUS Co.

Fredrik Pleijel

Chapter 8: The genetics of invertebrate species associated with Japanese Tsunami Marine Debris

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Abstract

Over 380 species have been collected from debris generated by the Great Japan Tsunami of 2011, many of which are challenging to identify by even well-trained taxonomists. Genetic analysis provides a tool to assist in identification and can also be used for monitoring North American waters for potential Japanese Tsunami Marine Debris (JTMD) associated invaders. Efficient DNA barcoding requires expert identification of voucher specimens that are sufficiently well preserved for molecular analysis. We conducted surveys on fouling organisms collected in Japan in habitats that might have contributed to the original JTMD rafting assemblage. To this purpose, we sequenced the mitochondrial cytochrome c oxidase subunit I (COI) gene from 130 morphospecies from 293 specimens collected in Miyako, Kesennuma, and Matsushima in 2015 and 2016 from settling panels deployed for 1 to 3 months. Sequences were aligned to Genbank sequences from putative conspecific, congeneric, confamilial, or consuperfamial specimens. Species identifications were considered confirmed when new sequences were within monophyletic clades with putative conspecifics. Identifications were reassigned when sequences fell into clearly defined clades lacking putative conspecifics. Species identifications were provisionally accepted when sequences from putative species that lack records in Genbank were nonetheless phylogenetically related to relevant higher taxa. Apparent species misidentifications within Genbank records were also noted. In this way, we generated sequences for 125 unique species from the Japanese fouling community, including 38 for which no prior sequence existed. Mussels ($n = 500$) collected in Oregon were identified by species-specific alleles at a nuclear locus, and were all native *Mytilus trossulus*. Species, and to a lesser extent haplotypes, not now known in North America can be a signature of tsunami-related invasion if detected in North America in the near future.


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Introduction

The purpose of the genetic component of the ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project was to generate DNA sequences from taxonomically validated specimens and use these sequences to detect Japanese species, potentially associated with the Great Japan Tsunami of 2011, in Pacific North American waters. This purpose has a clear relevance to the overall ADRIFT project, which seeks to assess ecological risks associated with potential colonization of Japanese species via JTMD. The chief purpose for genetic analysis has been to create baseline sequences for future investigations of the field environment or identification of individual samples. A survey in Japan aimed to obtain a thorough collection of fouling organisms' sequences to morphologically and genetically complement the existing collection of JTMD species, as well as to identify additional/new genetic strains that may have invasion potential.

Methods

Collections

Four types of collections were made for genetic analysis:

1. Specimens collected from JTMD debris items,
2. Fouling panels suspended in the waters of the tsunami-affected region in Japan,
3. Plankton collected in Yaquina Bay, Oregon, and
4. Bay mussels (*Mytilus* spp.) from Yaquina Bay and Coos Bay, Oregon.

Specimens were collected from JTMD objects arriving in North America and Hawaii as described in Chapter 7. Organisms on debris items were collected live or dead. Regardless of living condition when found, tissues were typically not preserved fresh. Rather, they may have been collected dead, died in transit, frozen, dried, or stored in formalin and/or ethanol in unknown concentrations. Individual or bulk specimens were shipped to the Williams College-Mystic Seaport Maritime Studies Program to be examined and sorted, and identified as narrowly as possible. Tissue subsamples were subsequently shipped to Moss Landing Marine Laboratories (MLML).

Samples in Japan were collected from fouling plate surveys conducted at several locations on the Tohoku coast (Figure 8-1). In 2015, fouling panels were installed in three different locations; Miyako (Iwate Prefecture), Kesennuma and Matsushima (Miyagi Prefecture) in July or August. In 2016, the fouling panels were installed in two different locations: Miyako and Minami-Sanriku (Miyagi Prefecture) in April to more closely align with the timing of the original tsunami event. All survey sites suffered serious damage by the tsunami after the Great East Japan Earthquake in 2011. Mussel collections are described in Chapter 13. Plankton was collected at dockside in Newport, Oregon by pumping approximately 1 m^3 of seawater through an 80 μm mesh.

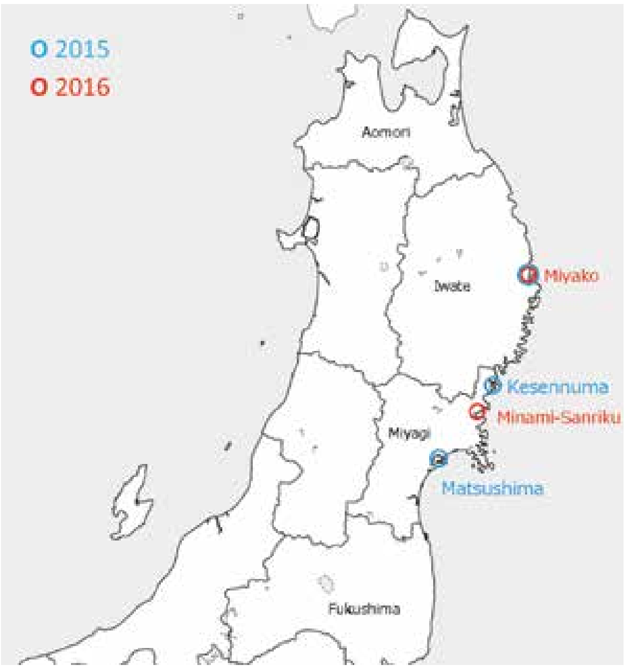

Figure 8-1. Fouling plate installation sites in 2015 (blue circles) and 2016 (red circles).


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Fouling panels consisted of 14 cm^2 hard plastic suspended from floating structures. The fouling panels installed at each site were retrieved in about 1 month (the first survey) and 3 months (the second survey) after installation (Table 8-1). The retrieved fouling panels were frozen at –20°C and later sorted and identified morphologically. Detailed initial identification was conducted in a local laboratory, and tissue subsamples were preserved in ethanol for DNA analysis and shipped to MLML.

Samples from North America were obtained from fouling panels deployed at the following sites: San Francisco Bay and Humboldt Bay, California; Yaquina Bay, Oregon; Willapa Bay, Grays Harbor, and Neah Bay, Washington; Prince Rupert, British Columbia; and Ketchikan, Alaska (see Chapter 13).

DNA extractions and PCR

DNA extractions of JTMD and Japanese fouling community vouchers and mussels used the MagJet Genomic DNA extraction kit (ThermoFisher K2721) following the manufacturer's instructions. Briefly, tissues were mechanically homogenized, lysed in Proteinase-K, and nucleic acids bound to magnetic beads for washing and elution. DNA was extracted from plankton using a similar method contained in the PowerSoil DNA extraction kit (MoBio), with DNA bound to silica resin in columns rather than magnetic beads. Polymerase chain reaction (PCR) was used to amplify the mitochondrial cytochrome c oxidase subunit 1 gene using standard primers and methods (Geller et al. ,2013).

DNA sequencing and sequence analysis

PCR products from JTMD-associated samples were indexed with Ion Torrent library tags and individual sample tags (short DNA strands), pooled, ligated to Ion Torrent specific adaptors, and sequenced on an Ion Torrent PGM sequencer. PCR products from Japanese vouchers were purified and Sanger-sequenced by Elim Biopharmaceuticals (Hayward), or purified at MLML using Ampure beads (Agencourt) prior to sequencing by Elim Biopharmaceuticals. Sequence editing and analysis were performed within the Geneious software package (Biomatters, Ltd., Auckland, New Zealand). Ion Torrent sequences were demultiplexed and assembled into contiguous sequences. Forward and reverse Sanger sequences were assembled, and trimmed of primers and low quality bases. Sequences were compared to related sequences in Genbank to ascertain taxonomic identities where prior records existed. For Japanese fouling community samples, sequences were aligned to Genbank sequences of putative conspecific, congeneric, confamilial, or consuperfamial specimens. Species identifications were considered confirmed when new sequences were within monophyletic clades with putative conspecific sequences. Identification was reassigned when sequences fell into clades of sequences of other species. Species identifications were provisionally accepted when sequences without conspecific records in Genbank were phylogenetically placed among putatively related taxa. Apparent misidentifications within Genbank records were also noted. Mussels were analyzed for diagnostic size variation in a PCR product within a byssal adhesive protein gene (Inoue et al., 1995).

Table 8-1. Schedule and locations of the field survey conducted in Japan.

		Placement (# of plates)	1 month (# of retrieved plates)	3 months (# of retrieved plates)
2015	Miyako	August 12 (30)	September 8 (15)	November 10 (15)
	Kesennuma	August 4 (10)	September 8 (5)	November 11 (5)
	Matsushima	July 24 (30)	September 10 (15)	November 12 (15)
2016	Miyako	April 26 (30)	May 31 (15)	August 2 (15)
	Minami-Sanriku	April 26 (30)	June 1 (14)	August 3 (15)

Plankton metagenetics

Genomic DNA was quantified using Picogreen and standardized to 5 ng µL^{-1}. The cytochrome c oxidase subunit I (COI) gene was amplified, in triplicate, using primers with adapters for Nextera barcode indices. Triplicates were pooled and purified with Agencourt Ampure beads. Purified, barcoded amplicons were pooled evenly by mass and sequenced on an Illumina MiSeq instrument. Plankton metagenetic sequences were analyzed with the 64 bit version of USEARCH 1.861 (Edgar, 2010).

Results

JTMD voucher sequencing

In total, 293 specimens from JTMD were sequenced on the Ion Torrent PGM instrument. One hundred and ninety-one templates were from PCR reactions with low yield and insufficient numbers of reads obtained. From the remainder, 29 morphological identifications comprising seven species were confirmed by comparing sequences to Genbank or the MLML invasive species genetic database. For example, 19 specimens identified only as the amphipod *Jassa* were refined to *Jassa marmorata*. Fifty-six specimens had no match to Genbank or a private database at MLML of invasive species found in California at a similarity of 95% or greater. These were initially morphologically identified as: Capitellidae, *Hydroides ezoensis*, Ampithoidae, *Caprella, Aetea* sp. B, *Alcyonidium, Bugula, Bugula neritina, Jellyella tuberculata, Membranipora*, Membraniporine sp. 2, *Scruparia, Tricellaria, Tubulipora misakiensis, Tubulipora* sp. A, *Tubulipora* sp. B, *Watersipora,* Ascidiacea, and "anemone". BLAST (Basic Local Alignment Search Tool) results showing 94% or greater similarity to Genbank or MLML records were *Jassa marmorata, Ampithoe lacertosa, Semibalanus cariosus,* and *Watersipora subtorquata*. We correlated low PCR and sequencing success to tissue quality (dried, discolored) or size (not visible or miniscule), and this was a major reason to shift focus to fresh material from Japan.

Japanese fouling community sequencing

Fouling plate communities varied with location; examples of the appearance of fouling panels in each location are illustrated in Table 8-2. The numbers of morphological specimens and samples for DNA analysis are shown in Table 8-3. The number of species found was highest in Matsushima, and lowest in Minami-Sanriku. More species were detected in the 3-month deployment survey than the 1-month deployment survey in all sites. Phylum Arthropoda (especially Class Malacostraca) dominated at all sites. A detailed list of all the species found in each survey is shown in Appendix 8-1. Most of the fouling organisms identified in the surveys are native to Japanese coasts.

We sequenced the mitochondrial COI gene from 130 morphospecies from 293 specimens that were collected in Miyako, Kesennuma, and Matsushima in 2015 and 2016 from settling panels deployed for 1 to 3 months. In this way, we generated sequences for 125 unique species from the Japanese fouling community, including 38 for which no prior sequence existed. Appendix 8-1 contains a list of specimens sequenced, their *a priori* morphological identification, and the genetic identification.

Table 8-2. Examples of retrieved fouling panels from each survey location and year.

Table 8-3. The number of specimens prepared for DNA and morphological analysis.

		The first survey		The second survey	
		Samples for DNA analysis	Morphological specimens	Samples for DNA analysis	Morphological specimens
Year 2	Miyako	31	14	51	16
	Kesennuma	35	9	65	14
	Matsushima	63	22	79	26
Year 3	Miyako	25	3	45	24
	Minami-Sanriku	14	5	37	13

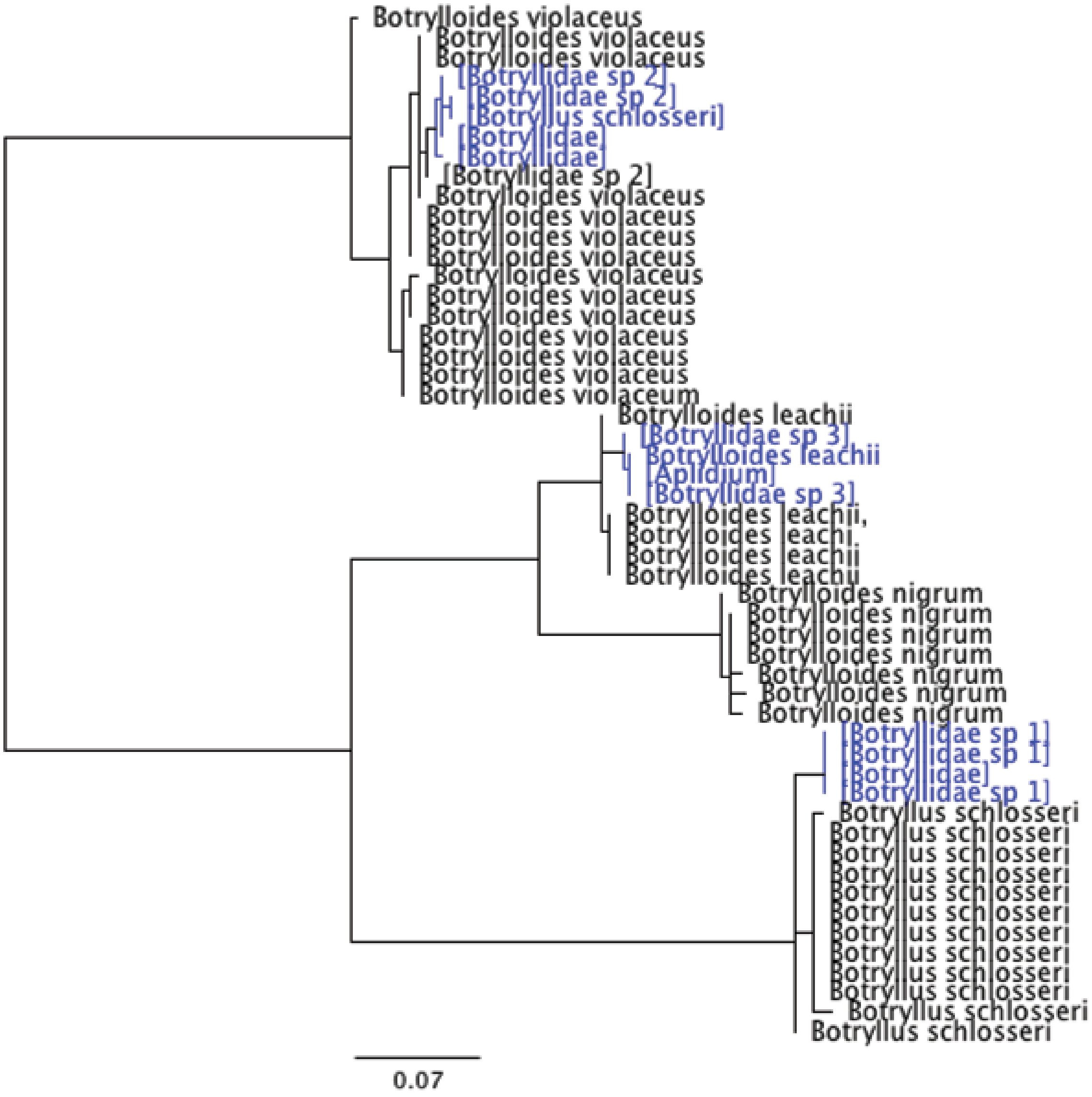

Figure 8-2. Maximum likelihood tree of cytochrome c oxidase subunit I (COI) sequences for specimens morphologically identified as Botryllidae, and one identified as *Aplidium*. Blue font enclosed by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

Sequences from each putative morphospecies were aligned and phylogenetically analyzed. By noting inclusion of novel sequences in unambiguous clades, some low-resolution morphological identifications could be clarified. For example, specimens variously identified as Botryllidae, Botryllidae sp., etc., were determined to be *Botrylloides violaceus*, *Botrylloides leachii*, or *Botryllus schlosseri*. Conversely, one specimen positively identified morphologically as *Botryllus schlosseri* was shown to be *Botrylloides violaceus*. Finally, sequences that might indicate contamination of tissues or DNA were uncovered, such as the morphological identification of a specimen as *Aplidium* that was genetically *Botrylloides leachi* (Figure 8-2).

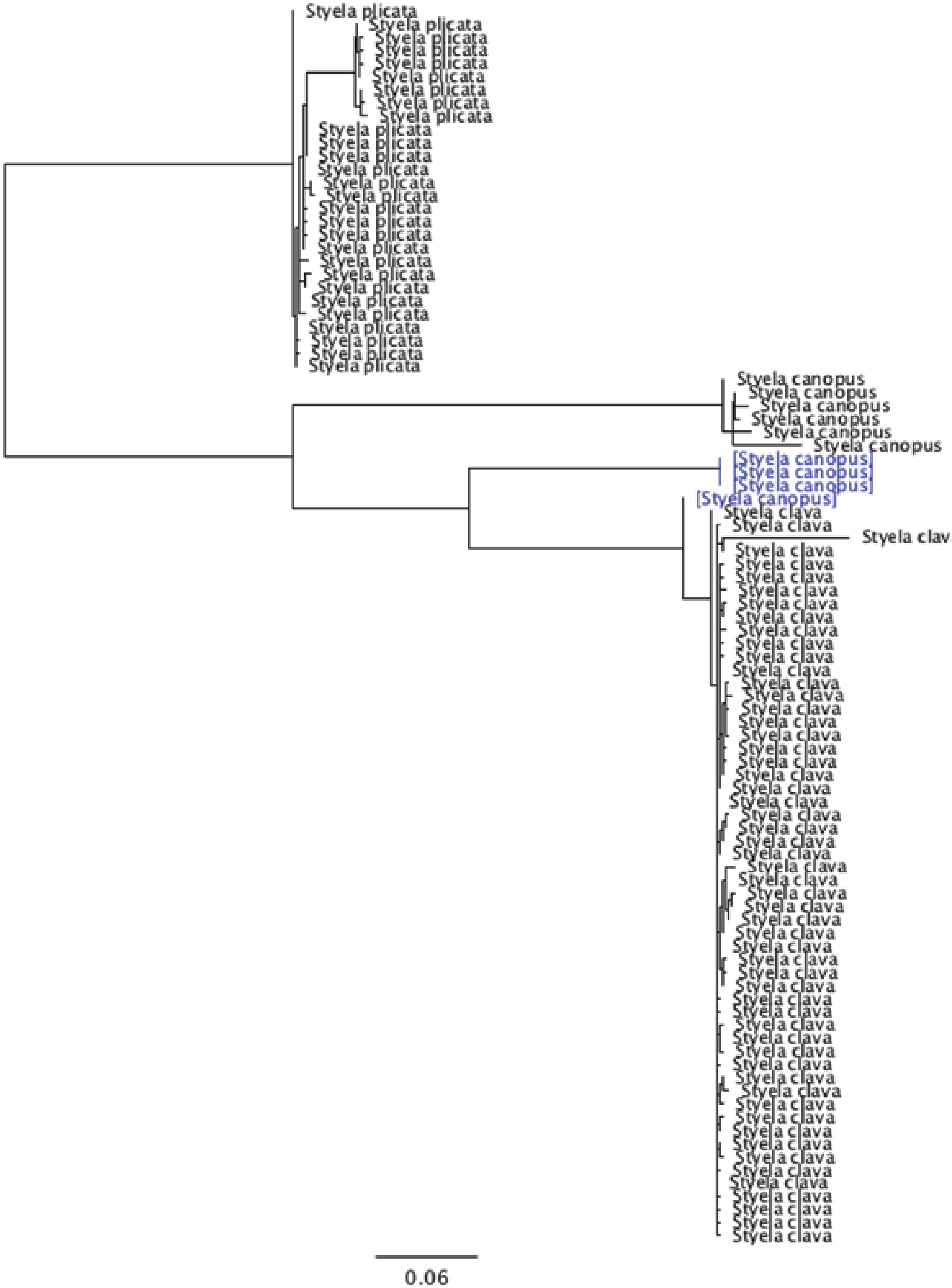

Figure 8-3. Relationships of Japanese specimens identified as *Styela canopus* to existing Genbank records. Blue font enclosed by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

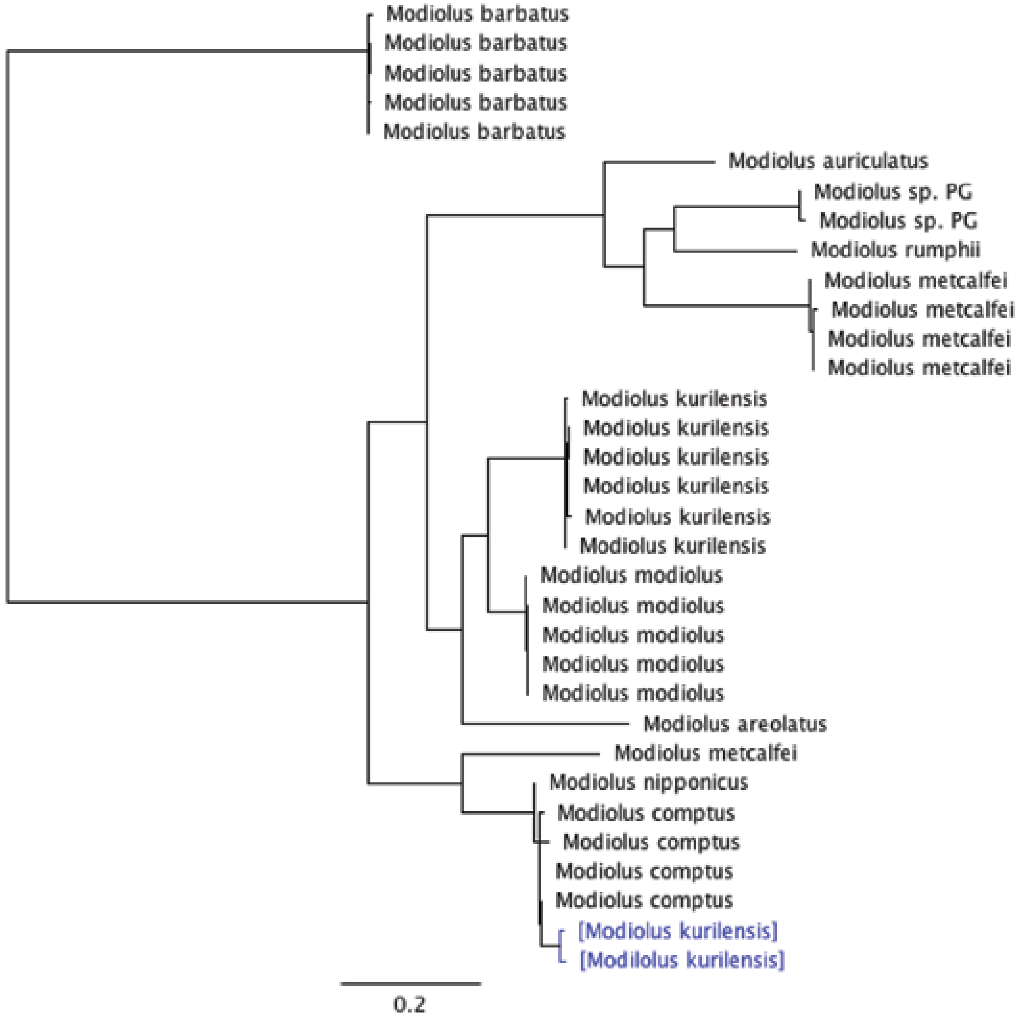

Figure 8-4. Specimens identified as *Modiolus kurilensis* are related to *M. nipponicus* or *M. comptus*. Blue font enclosed by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

Modiolus kurilensis

In other cases, morphological identifications suggested hidden diversity within nominal species. No specimens identified by morphology as *Styela canopus* clustered with Genbank entries for this species, but did so as sister to *S. clava*. Thus, these specimens may be *S. clava* or a cryptic species related to *S. clava* (Figure 8-3).

Another outcome example was the reassignment of sequences from the morphological prior identification to an ambiguous genetic assignment. Specimens identified as *Modiolus kurilensis* were not related to Genbank records of this name, but ambiguously to *Modiolus nipponicus* or *M. comptus* (Figure 8-4).

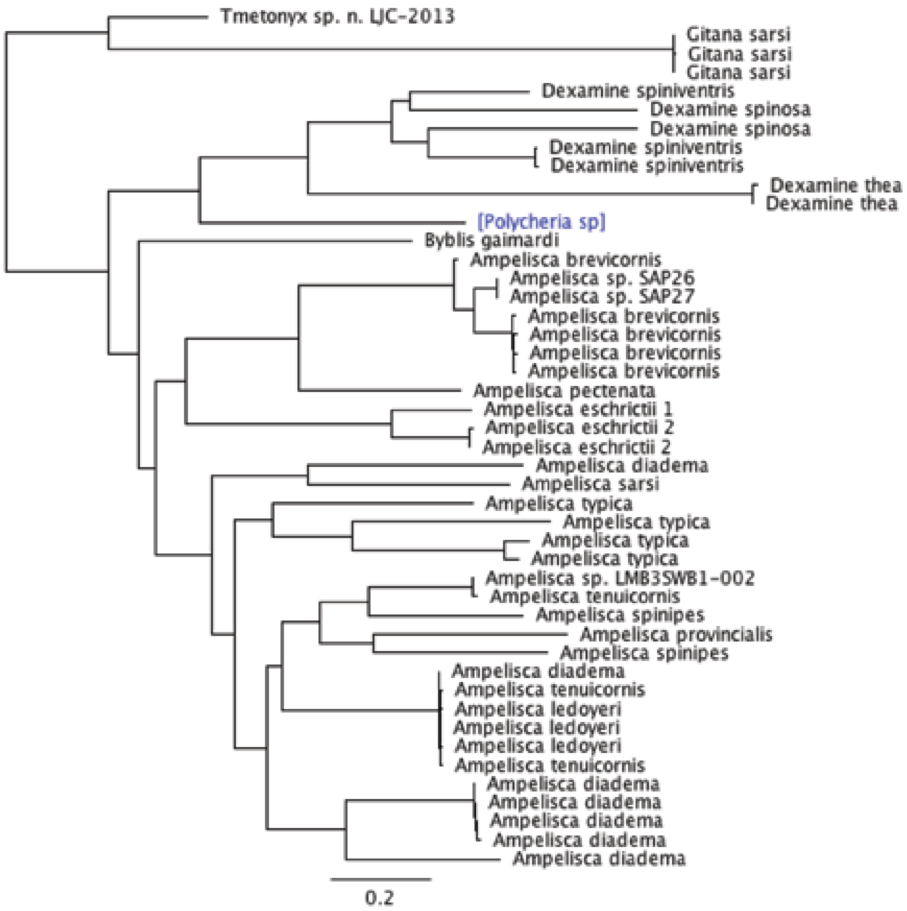

Figure 8-5. Morphologically identified *Polycheria* was phylogenetically basal to other Dexaminidae among the Gammaridea, and therefore this identification was accepted. Blue font enclosed by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

Finally, in many cases Genbank was sparse for records closely related to a Japanese voucher, and phylogenetic analysis may only have shown that the novel sequence fit among confamilials or consuperfamilials. In these cases, there was no genetic evidence that contradicted the morphological identification, which was thus provisionally accepted. For example, the amphipod called *Polycheria* fits at the base of other members of the family Dexaminidae (Figure 8-5) and so is plausibly *Polycheria*.

North American surveys

All 500 mussels collected in Yaquina Bay and Coos Bay (250 each) were identified as *Mytilus trossulus*, a native of the Northeastern Pacific Ocean, using the method of Inoue et al. (1995). There were no incidences of the JTMD-associated non-indigenous species *Mytilus galloprovincialis*.

Three sites in Yaquina Bay (Hog's Marina, Port of Newport, and Embarcadero) yielded 211,466 total reads and 64,972 paired-end reads of COI. These clustered into 209 OTUs (operational taxonomic units) using a 97% similarity threshold, and OTUs matched Genbank at 95% or better for 66 OTU. Removing bacteria and unidentified phytoplankton left 78 OTU (Table 8-4). Clustering was also performed with unpaired reads to increase available reads (since not all reads could be paired), which increased the number of OTU to 297. Rarefaction analysis shows that OTU accumulation had not reached an asymptote, suggesting that deeper sequencing will greatly increase the number of taxa recovered (Figure 8-6).

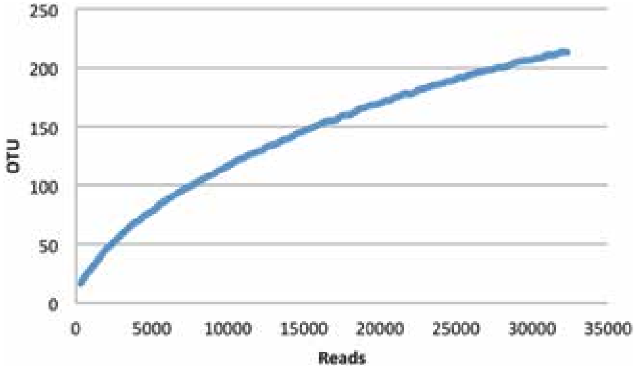

Figure 8-6. Yaquina Bay plankton. Rarefaction of OTUs (operational taxonomic units) recovered with increasing read abundance, using 165,809 unique reads, clustered at a 97% similarity threshold, and omitting any OTU with group size of 1 read.

Table 8-4. OTU identified COI sequences from pooled zooplankton samples from Yaquina Bay, Oregon.

Species	**Taxonomic group**	**Species**	**Taxonomic group**
Anthopleura elegantissima	Anthozoa	*Hematodinium* sp.	Dinoflagellate
Angulus nuculoides	Bivalvia	cf. *Protoperidinium* sp.	Dinoflagellate
Hiatella sp.	Bivalvia	*Pyrocystis lunula*	Dinoflagellate
Kellia suborbicularis	Bivalvia	*Aplysiopsis enteromorphae*	Gastropoda
Melanochlamys diomedea	Gastropoda	*Assiminea* sp.	Gastropoda
Mytilus californianus	Bivalvia	*Dendronotus venustus*	Gastropoda
Mytilus trossulus	Bivalvia	*Diaulula sandiegensis*	Gastropoda
Neaeromya rugifera	Bivalvia	*Doris montereyensis*	Gastropoda
Hemigrapsus oregonensis	Brachyura	*Flabellina verrucosa*	Gastropoda
Lophopanopeus bellus	Brachyura	*Gastropteron pacificum*	Gastropoda
Pandalus jordani	Caridea	*Hermissenda crassicornis*	Gastropoda
Amphibalanus improvisus	Cirripedia	*Limacina helicina*	Gastropoda
Amphibalanus sp.	Cirripedia	*Littorina plena*	Gastropoda
Balanus crenatus	Cirripedia	*Lottia pelta*	Gastropoda
Balanus glandula	Cirripedia	*Margarites pupillus*	Gastropoda
Chthamalus dalli	Cirripedia	*Olivella biplicata*	Gastropoda
Pollicipes polymerus	Cirripedia	*Olivella baetica*	Gastropoda
Evadne nordmanni	Cladocera	*Rictaxis punctocaelatus*	Gastropoda
Podon leuckartii	Cladocera	*Stiliger fuscovittatus*	Gastropoda
Acartia californiensis	Copepoda	*Williamia peltoides*	Gastropoda
Acartia sp.	Copepoda	*Merluccius productus*	Hake
Acartia tonsa	Copepoda	*Clytia* sp.	Hydrozoa
Calanus pacificus	Copepoda	*Obelia dichotoma*	Hydrozoa
Centropages abdominalis	Copepoda	*Poseidonemertes collaris*	Nemertea
Ctenocalanus vanus	Copepoda	*Ophiopholis kennerlyi*	Ophiuroidea
Cyclops kikuchii	Copepoda	*Dictyosiphon* sp.	Phaeophyta
Eucalanus californicus	Copepoda	*Ectocarpus fasciculatus*	Phaeophyta
Oithona similis	Copepoda	*Ectocarpus siliculosus*	Phaeophyta
Orthione griffenis	Isopoda	*Myrionema balticum*	Phaeophyta
Paracalanus parvus	Copepoda	*Myrionema strangulans*	Phaeophyta
Pseudocalanus mimus	Copepoda	*Chone magna*	Polychaeta
Attheya longicornis	Diatom	*Leitoscoloplos pugettensis*	Polychaeta
Berkeleya fennica	Diatom	*Nereis vexillosa*	Polychaeta
Ditylum brightwellii	Diatom	*Platynereis* sp.	Polychaeta
Eucampia zodiacus	Diatom	*Polydora cornuta*	Polychaeta
Fragilaria striatula	Diatom	*Scoloplos acmeceps*	Polychaeta
Grammonema striatula	Diatom	*Thaleichthys pacificus*	Smelt
Melosira nummuloides	Diatom	*Citharichthys stigmaeus*	Speckled sanddab
Pseudo-nitzschia pungens	Diatom		
Stephanopyxis turris	Diatom		

Nancy Treneman

Discussion

The DNA sequences generated herein provide tools for detection and monitoring Japanese species beyond their natural biogeographic limits. Methods such as metabarcoding, as illustrated here, or probing of environmental samples by qPCR (Mackie and Geller, 2010), will allow investigation of large volumes of biomass. Metabarcoding of the Yaquina Bay sample did not reveal any Japanese species that were not already known as introduced to the area. Similarly, all mussels identified in Coos Bay and Yaquina Bay were native *Mytilus trossulus*. These results provide a baseline with which to compare future measurements: appearance of taxa identified genetically or morphologically from JTMD or the Japanese fouling community could be signals of a tsunami-related invasion.

The absence of *Mytilus galloprovincialis* from Oregon was striking given the abundance of this species on JTMD objects. This species is well established in California, but ongoing study of its distribution indicates a northern boundary in the US currently below the Oregon border (Fofonoff et al., 2003). The potential saltatory appearance of *M. galloprovincialis* at Oregon sites is another potential tsunami-related invasion signal to monitor. Population genetic comparisons of any such Oregon invasions to California populations will provide a second level of testing.

The results of phylogenetic analyses presented in Appendix 8-1 revealed many cases of potential cryptic species. In addition, many specimens that were barcoded were not fully identified to the species level because DNA barcodes for the specific assignment are not yet available. Parallel morphological vouchers were sent to Williams College in 2016 to be further distributed to taxonomic experts. As these specimens are identified or described, this project will contribute to the refinement of taxonomic knowledge of the Japanese biota and, not unimportantly, to the suite of species that are common invaders world-wide.

The major achievement is the establishment of a DNA barcode dataset for many taxa delivered or potentially delivered to the Pacific coast of North America by JTMD. These sequences provide a framework for detection and association of new invasions with JTMD. The analysis of environmental samples collected under ADRIFT can provide a baseline for comparison for future studies.

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Chapter 8 Appendices

Appendix 8-1. Species morphologically identified from fouling panel surveys in Japan

Appendix 8-2. Morphological and genetic identification of Japanese fouling community species

Appendix 8-1. Species identified from fouling panel surveys in Japan

Identified species in Miyako (Year 2)			
The first survey			
	Phylum	**Class**	**Species**
1	CNIDARIA	HYDROZOA	*Halecium pusillum*
2	BRYOZOA	CHEILOSTOMATIDA	*Celleporina* sp.
3	ANNELIDA	POLYCHAETA	*Hydroides ezoensis*
4			*Neodexiospira alveolata*
5	ARTHROPODA	MAXILLOPODA	*Amphibalanus improvisus*
6			*Perforatus perforatus*
7		MALACOSTRACA	*Ampithoe* sp. 1
8			*Aoroides* sp.
9			*Monocorophium acherusicum*
10			*Ericthonius convexus*
11			*Jassa slatteryi*
12			*Paradexamine* sp.
13			*Polycheria* sp.
14			*Melita* sp.
15			*Leucothoe nagata*
16			*Stenothoe* sp. 2
17			*Stenothoe* sp. 1
18			*Caprella equilibra*
19			*Caprella mutica*
20			*Caprella scaura*
21			*Paranthura japonica*
22			*Ianiropsis serricaudis*
23			*Synidotea hikigawaensis*
24			*Cymodoce japonica*
25			*Zeuxo* sp. (aff. *Z. coralensis*)
26	CHORDATA	ASCIDIACEA	*Diplosoma listerianum*
27			*Distaplia dubia*
28			Botryllidae gen. sp. 1
29			Botryllidae gen. sp. 2
30			Botryllidae gen. sp. 3
31			Botryllidae gen. sp. 4

Identified species in Miyako (Year 2)			
The second survey			
	Phylum	**Class**	**Species**
1	PORIFERA	DEMOSPONGIAE	*Halichondria* sp.
2	CNIDARIA	HYDROZOA	*Halecium pusillum*
3	NEMERTINEA	ENOPLA	*Nemertellina yamaokai*
4	BRYOZOA	CHEILOSTOMATIDA	*Membranipora* sp.
5			*Tricellaria inopinata*
6			*Celleporaria* sp.
7			*Celleporina porosissima*
8			*Escharella takatukii*
9	MOLLUSCA	GASTROPODA	*Sakuraeolis* sp.
10		BIVALVIA	*Mytilus galloprovincialis*
11			*Musculista senhousia*
12	ANNELIDA	POLYCHAETA	*Hermilepidonotus helotypus*
13			*Anaitides* sp.
14			*Eulalia viridis japanensis*
15			*Syllis* sp.
16			*Nereis pelagica*
17			*Platynereis bicanaliculata*
18			*Arabella* sp.
19			*Nicolea* sp.
20			*Hydroides ezoensis*
21	ARTHROPODA	PYCNOGONIDEA	*Anoplodactylus crassus*
22		MAXILLOPODA	*Balanus trigonus*
23			*Amphibalanus amphitrite*
24			*Amphibalanus improvisus*
25			*Fistulobalanus albicostatus*
26			*Perforatus perforatus*
27		MALACOSTRACA	*Ampithoe* sp. 1
28			*Aoroides* sp.
29			*Monocorophium acherusicum*
30			*Gammaropsis japonica*
31			*Ericthonius convexus*
32			*Jassa slatteryi*
33			*Polycheria* sp.
34			*Stenothoe* sp. 2
35			*Caprella equilibra*
36			*Caprella mutica*
37			*Caprella scaura*
38			*Paranthura japonica*
39			*Ianiropsis serricaudis*
40			*Synidotea hikigawaensis*
41			*Cymodoce japonica*
42			*Zeuxo* sp. (aff. *Z. maledivensis*)
43	CHORDATA	ASCIDIACEA	*Distaplia dubia*
44			*Ciona savignyi*
45			*Perophora japonica*
46			*Ascidia* sp.
47			*Botryllus schlosseri*
48			Botryllidae gen. sp. 1
49			Botryllidae gen. sp. 2
50			Botryllidae gen. sp. 3
51			*Styela* sp.

Appendix 8-1. Species identified from fouling panel surveys in Japan (cont'd)

	Identified species in Kesennuma (Year 2)		
	The first survey		
	Phylum	**Class**	**Species**
1	CNIDARIA	ANTHOZOA	*Diadumene lineata*
2	BRYOZOA	CHEILOSTOMATIDA	*Tricellaria inopinata*
3			*Celleporina* sp.
4			*Watersipora cucullata*
5	MOLLUSCA	BIVALVIA	*Anomia chinensis*
6			*Crassostrea gigas*
7			*Protothaca jedoensis*
8	ANNELIDA	POLYCHAETA	*Syllis* sp.
9			*Hydroides ezoensis*
10			*Neodexiospira alveolata*
11	ARTHROPODA	MAXILLOPODA	*Chthamalus challengeri*
12			*Balanus trigonus*
13			*Amphibalanus improvisus*
14			*Perforatus perforatus*
15			*Megabalanus rosa*
16		MALACOSTRACA	*Ampithoe* sp. 2
17			*Gammaropsis japonica*
18			*Ericthonius convexus*
19			*Jassa slatteryi*
20			*Polycheria* sp.
21			*Pontogeneia* sp.
22			*Maera pacifica*
23			*Melita* sp.
24			*Gitanopsis* sp.
25			*Anamixis* sp.
26			*Parapleustes* sp.
27			*Stenothoe* sp. 2
28			*Caprella equilibra*
29			*Paranthura japonica*
30			*Ianiropsis serricaudis*
31			*Cirolana harfordi japonica*
32	CHORDATA	ASCIDIACEA	*Diplosoma listerianum*
33			Botryllidae gen. sp. 1
34			Botryllidae gen. sp. 2
35			*Symplegma reptans*

	Identified species in Kesennuma (Year 2)		
	The second survey		
	Phylum	**Class**	**Species**
1	PORIFERA	CALCAREA	*Grantessa* sp.
2		DEMOSPONGIAE	*Halichondria* sp.
3	CNIDARIA	ANTHOZOA	ACTINIARIA
4	NEMERTINEA	ENOPLA	*Nemertellina yamaokai*
5	BRYOZOA	CHEILOSTOMATIDA	*Amathia distans*
6			*Tricellaria occidentalis*
7			*Celleporina porosissima*
8			*Escharella takatukii*
9			*Watersipora cucullata*
10	MOLLUSCA	GASTROPODA	*Mitrella bicincta*
11		BIVALVIA	*Mytilus galloprovincialis*
12			*Musculus cupreus*
13			*Crassostrea gigas*
14	ANNELIDA	POLYCHAETA	*Halosydna brevisetosa*
15			*Lepidonotus elongatus*
16			*Eulalia viridis japanensis*
17			*Eulalia* sp.
18			*Nereiphylla castanea*
19			*Syllis* sp.
20			*Neanthes caudata*
21			*Nereis multignatha*
22			*Nereis neoneanthes*
23			*Platynereis bicanaliculata*
24			*Armandia* sp.
25			*Polyophthalmus pictus*
26			*Nicolea* sp.
27			*Hydroides ezoensis*
28			*Neodexiospira alveolata*
29	ARTHROPODA	MAXILLOPODA	*Balanus trigonus*
30			*Amphibalanus improvisus*
31			*Perforatus perforatus*
32			*Megabalanus rosa*
33		MALACOSTRACA	*Ampithoe* sp. 1
34			*Aoroides longimerus*
35			*Monocorophium sextonae*
36			*Monocorophium uenoi*
37			*Gammaropsis japonica*
38			*Ericthonius convexus*
39			*Jassa slatteryi*
40			*Podocerus* sp.
41			*Polycheria* sp.
42			*Maera pacifica*
43			*Maera* sp.
44			*Melita rylovae*
45			*Gitanopsis* sp.
46			*Parapleustes* sp.
47			*Stenothoe* sp. 2
48			*Orchomene* sp.
49			*Gypsiphimedia mala*
50			*Caprella equilibra*
51			*Caprella polyacantha*
52			*Caprella penantis*
53			*Caprella scaura*
54			*Paranthura japonica*
55			*Ianiropsis serricaudis*
56			*Cirolana harfordi japonica*
57			*Dynoides dentisinus*
58			*Eualus leptognathus*
59	CHORDATA	ASCIDIACEA	*Aplidium* sp.
60			*Diplosoma listerianum*
61			*Ciona intestinalis* type A
62			*Ciona savignyi*
63			*Ascidia sydneiensis*
64			Botryllidae gen. sp. 2
65			*Styela canopus*

Appendix 8-1. Species identified from fouling panel surveys in Japan (cont'd)

Identified species in Matsushima (Year 2)			
The first survey			
	Phylum	**Class**	**Species**
1	PORIFERA	CALCAREA	*Grantessa* sp.
2	CNIDARIA	HYDROZOA	*Eudendrium* sp.
3		ANTHOZOA	*Diadumene lineata*
4			*Anthopleura* sp.
5	BRYOZOA	CHEILOSTOMATIDA	*Amathia distans*
6			*Bugula neritina*
7			*Bugula stolonifera*
8	MOLLUSCA	GASTROPODA	*Dendrodoris fumata*
9		BIVALVIA	*Musculista senhousia*
10			*Chlamys* sp.
11			*Anomia chinensis*
12			*Crassostrea gigas*
13			*Theora fragilis*
14	ANNELIDA	POLYCHAETA	*Lepidonotus elongatus*
15			*Anaitides* sp.
16			*Eulalia viridis*
17			*Proceraea* sp.
18			*Syllis* sp.
19			*Neanthes caudata*
20			*Nereis multignatha*
21			*Nereis neoneanthes*
22			*Platynereis bicanaliculata*
23			*Dorvillea* sp.
24			*Nicolea* sp.
25			Terebellidae gen. sp.
26			*Pseudopotamilla* sp.
27			*Sabella* sp.
28			*Hydroides ezoensis*
29	ARTHROPODA	PYCNOGONIDA	*Callipallene* sp.
30			*Anoplodactylus crassus*
31		MAXILLOPODA	*Amphibalanus improvisus*
32		MALACOSTRACA	*Ampithoe* sp. 1
33			*Aoroides longimerus*
34			*Corophium acherusicum*
35			*Jassa slatteryi*
36			*Paradexamine* sp.
37			*Polycheria* sp.
38			*Melita rylovae*
39			*Gitanopsis* sp.
40			*Anamixis* sp.
41			*Colomastix* sp.
42			*Leucothoe nagatai*
43			*Parapleustes* sp.
44			*Stenothoe* sp. 1
45			*Stenothoe* sp. 2
46			*Liljeborgia serrata*
47			*Orchomene* sp.
48			*Cypsiphimedia mala*
49			*Caprella penantis*
50			*Caprella scaura*
51			*Paranthura japonica*
52			*Ianiropsis serricaudis*
53			*Cymodoce japonica*
54			*Eualus leptognathus*
55			*Heptacarpus rectirostris*
56	CHORDATA	ASCIDIACEA	*Didemnum* sp.
57			*Ciona intestinalis* type A
58			*Ciona savignyi*
59			*Ascidia zara*
60			*Ascidia sydneiensis*
61			Botryllidae gen. sp.
62			*Molgula manhattensis*
63		OSTEICHTHYES	*Tridentiger trigonocephalus*

Identified species in Matsushima (Year 2)			
The second survey			
	Phylum	**Class**	**Species**
1	PORIFERA	CALCAREA	*Grantessa* sp.
2		DEMOSPONGIAE	*Halichondria sitiens*
3			*Haliclona* sp.
4	CNIDARIA	HYDROZOA	*Eudendrium* sp.
5		ANTHOZOA	*Diadumene lineata*
6	NEMERTINEA	ANOPLA	*Procephalothrix* sp.
7	KAMPTOZOA		*Barentsia discreta*
8	BRYOZOA	CHEILOSTOMATIDA	*Amathia distans*
9			*Membranipora* sp. 2
10			*Bugula neritina*
11			*Tricellaria inopinata*
12			*Celleporina porosissima*
13			*Cryptosula pallasiana*
14			*Escharella takatukii*
15	MOLLUSCA	GASTROPODA	*Brachystomia minutiovum*
16			*Dendrodoris fumata*
17		BIVALVIA	*Mytilus galloprovincialis*
18			*Modiolus kurilensis*
19			*Musculista senhousia*
20			*Chlamys farreri nipponensis*
21			*Chlamys* sp.
22			*Anomia chinensis*
23			*Crassostrea gigas*
24	ANNELIDA	POLYCHAETA	*Harmothoe* sp.
25			*Halosydna brevisetosa*
26			*Lepidonotus elongatus*
27			*Nereiphylla castanea*
28			*Nereis multignatha*
29			*Platynereis bicanaliculata*
30			*Marphysa* sp.
31			*Amphitrite* sp.
32			*Sabella* sp.
33			*Hydroides ezoensis*
34	ARTHROPODA	PYCNOGONIDA	*Anoplodactylus crassus*
35		MAXILLOPODA	*Balanus trigonus*
36			*Amphibalanus amphitrite*
37			*Amphibalanus eburneus*
38			*Amphibalanus improvisus*
39			*Fistulobalanus albicostatus*
40		MALACOSTRACA	*Ampithoe tarasovi*
41			*Ampithoe* sp. 2
42			*Aoroides longimerus*
43			*Monocorophium acherusicum*
44			*Monocorophium uenoi*
45			*Jassa slatteryi*
46			*Paradexamine* sp.
47			*Maera* sp.
48			*Melita rylovae*
49			*Gitanopsis* sp.
50			*Anamixis* sp.
51			*Colomastix* sp.
52			*Leucothoe nagatai*
53			*Parapleustes* sp.
54			*Stenothoe* sp. 1
55			*Stenothoe* sp. 2
56			*Liljeborgia serrata*
57			*Orchomene* sp.
58			*Cypsiphimedia mala*
59			*Caprella scaura*
60			*Paranthura japonica*
61			*Ianiropsis serricaudis*
62			*Cymodoce japonica*
63			*Dynoides dentisinus*
64			*Eualus leptognathus*
65			*Heptacarpus rectirostris*
66			*Halicarcinus messor*
67			*Hemigrapsus takanoi*
68	CHORDATA	ASCIDIACEA	*Aplidium* sp.
69			*Didemnum* sp.
70			*Ciona intestinalis* type A
71			*Ciona savignyi*
72			*Ascidia sydneiensis*
73			*Ascidia zara*
74			Botryllidae gen. sp. 1
75			Botryllidae gen. sp. 2
76			*Styela canopus*
77			*Molgula manhattensis*
78		OSTEICHTHYES	*Tridentiger trigonocephalus*

Appendix 8-1. Species identified from fouling panel surveys in Japan (cont'd)

Identified species in Miyako (Year 3)			
The first survey			
	Phylum	**Class**	**Species**
1	BRYOZOA	CHEILOSTOMATIDA	*Tricellaria inopinata*
2			*Celleporina porosissima*
3			*Microporella* sp.
4	MOLLUSCA	GASTROPODA	*Barleeia angustata*
5			PROSOBRANCHIA fam. gen. sp.
6		BIVALVIA	*Mytilus galloprovincialis*
7			*Hiatella orientalis*
8	ANNELIDA	POLYCHAETA	*Lumbrineridae* gen. sp.
9			*Serpulidae* gen. sp.
10	ARTHROPODA	MAXILLOPODA	*Amphibalanus eburneus*
11		MALACOSTRACA	*Ampithoe* sp. 1
12			*Aoroides* sp.
13			*Monocorophium acherusicum*
14			*Gammaropsis japonica*
15			*Ericthonius convexus*
16			*Jassa slatteryi*
17			*Pontogeneia* sp.
18			*Stenothoe* sp. aff. *dentirama*
19			*Caprella equilibra*
20			*Caprella mutica*
21			*Caprella scaura*
22			*Paranthura japonica*
23			*Zeuxo* sp.
24	CHORDATA	ASCIDIACEA	*Distaplia dubia*
25			Botryllidae gen. sp.

Identified species in Miyako (Year 3)			
The second survey			
	Phylum	**Class**	**Species**
1	PORIFERA	DEMOSPONGIAE	*Halichondria* sp.
2	NEMERTINEA	ANOPLA	*Nemertellina yamaokai*
3	BRYOZOA	CHEILOSTOMATIDA	*Tricellaria inopinata*
4			*Celleporina porosissima*
5			*Pacificincola perforata*
6			*Escharella takatukii*
7	MOLLUSCA	GASTROPODA	*Lirularia iridescens*
8		BIVALVIA	*Mytilus galloprovincialis*
9			*Vilasina decorata*
10			*Musculus cupreus*
11			*Hiatella orientalis*
12	ANNELIDA	POLYCHAETA	*Harmothoe* sp.
13			*Syllis* sp.
14			*Megasyllis nipponica*
15			*Nereis vexillosa*
16			*Serpulidae* gen. sp.
17	ARTHROPODA	MALACOSTRACA	*Ampithoe lacertosa*
18			*Aoroides* sp.
19			*Monocorophium acherusicum*
20			*Gammaropsis japonica*
21			*Ericthonius convexus*
22			*Jassa slatteryi*
23			*Podocerus* sp.
24			*Polycheria* sp.
25			*Pontogeneia* sp.
26			*Stenothoe* sp. aff. *dentirama*
27			*Gordonodius zelleri*
28			*Caprella equilibra*
29			*Caprella mutica*
30			*Caprella scaura*
31			*Paranthura japonica*
32			*Ianiropsis serricaudis*
33			*Gymodoce japonica*
34			*Zeuxo* sp.
35	CHORDATA	ASCIDIACEA	*Aplidium* sp.
36			*Diplosoma listerianum*
37			*Distaplia dubia*
38			*Ciona savignyi*
39			*Perophora* sp.
40			*Ascidiella aspersa*
41			*Botrylloides violaceus*
42			*Botryllus* sp.
43			Botryllidae gen. sp.
44			Botryllidae gen. sp. 2
45			Styelidae gen. sp.

Appendix 8-1. Species identified from fouling panel surveys in Japan (cont'd)

Identified species in Minami-Sanriku (Year 3)			
The first survey			
	Phylum	**Class**	**Species**
1	CNIDARIA	HYDROZOA	*Obelia* sp.
2	MOLLUSCA	GASTROPODA	*Mitrella bicincta*
3		BIVALVIA	*Mytilus galloprovincialis*
4	ARTHROPODA	MALACOSTRACA	*Ampithoe* sp. 1
5			*Ericthonius convexus*
6			*Jassa marmorata*
7			*Jassa slatteryi*
8			*Jassa* sp.
9			*Stenothoe* sp. aff. *dentirama*
10			*Stenothoe* sp. 1
11			*Caprella californica*
12			*Caprella equilibra*
13			*Caprella mutica*
14			*Caprella penantis*

Identified species in Minami-Sanriku (Year 3)			
The second survey			
	Phylum	**Class**	**Species**
1	CNIDARIA	HYDROZOA	*Obelia* sp. (almost hydranth lacking)
2	NEMERTINEA	ENOPLA	*Nemertellina yamaokai*
3			*Tetrastemma nigrifrons*
4	BRYOZOA	CHEILOSTOMATIDA	*Tricellaria inopinata*
5			*Celleporina porosissima*
6			*Watersipora subatra*
7	MOLLUSCA	GASTROPODA	*Sakuraeolis* sp.
8		BIVALVIA	*Mytilus galloprovincialis*
9			*Musculus cupreus*
10	ANNELIDA	POLYCHAETA	*Autolytus* sp.
11			*Syllis* sp.
12			*Nereis pelagica*
13			*Platynereis bicanaliculata*
14			*Terebellidae* gen. sp.
15	ARTHROPODA	MAXILLOPODA	*Perforatus perforatus*
16			*Megabalanus rosa*
17		MALACOSTRACA	*Ampithoe lacertosa*
18			*Ampithoe* sp. 2
19			*Aoroides longimerus*
20			*Gammaropsis japonica*
21			*Ericthonius convexus*
22			*Jassa marmorata*
23			*Jassa slatteryi*
24			*Jassa staudei*
25			*Polycheria* sp.
26			*Stenothoe* sp. aff. *dentirama*
27			*Caprella equilibra*
28			*Caprella mutica*
29			*Caprella penantis*
30			*Paranthura japonica*
31			*Ianiropsis serricaudis*
32			*Gymodoce japonica*
33	CHORDATA	ASCIDIACEA	*Didemnum* sp.
34			*Diplosoma listerianum*
35			*Distaplia dubia*
36			*Ascidia sydneiensis*
37			*Botryllidae* gen. sp.

Appendix 8-2. Morphological and genetic identification of Japanese fouling community species

Specimen	Morphological assignment	Genetic result and comments
M3_K-13.06	Actiniaria	*Aiptasia* possibly *pulchella*
M3_K-13.07-11	Actiniaria	*Aiptasia* possibly *pulchella*
M3_S-10.01	*Amathia distans*	*Amathia distans* provisionally accepted
M3_S-10.02	*Amathia distans*	Amathia distans provisionally accepted
M3_S-10.03	*Amathia distans*	Amathia distans provisionally accepted
M3_M-13.05	*Amphibalanus amphitrite*	*Amphibalanus amphitrite* confirmed
M3_M-27.05	*Amphibalanus amphitrite*	*Caprella mutica, probable contaminant*
M3_S-77.01	*Amphibalanus amphitrite*	*Amphibalanus amphitrite* confirmed
M3_S-63.01	*Amphibalanus eburneus*	*Amphibalanus eburneus* confirmed
M3_M-8.01	*Amphibalanus improvisus*	*Amphibalanus improvisus* confirmed
M3_M-8.02	*Amphibalanus improvisus*	*Amphibalanus improvisus* confirmed
M3_M-8.03	*Amphibalanus improvisus*	*Amphibalanus improvisus* confirmed
M3_S-41.01	*Amphitrite* sp.	*Amphitrite* sp. provisionally accepted
M3_S-41.02	*Amphitrite* sp.	*Amphitrite* sp. provisionally accepted
M3_M-13.01	*Ampithoe* sp. 1	*Ampithoe tarasovi*
M3_M-13.02	*Ampithoe* sp. 1	*Ampithoe tarasovi*
M3_M-36.05	*Ampithoe* sp. 1	*Ampithoe tarasovi*
M3_S-17.01	*Ampithoe* sp. 2	*Ampithoe* sp.
M3_S-17.02-04	*Ampithoe* sp. 2	*Ampithoe* sp.
M3_K-64.02	*Ampithoe* sp1	*Fistulobalanus albicostatus*
M3_M-19.01-02	*Anaitides* sp.	Phyllodocidae, possible conflict with *Anaitides* in Genbank
M3_S-42.01	*Anamixis* sp.	*Ampithoe tarasovi*
M3_S-42.02	*Anamixis* sp.	*Ampithoe tarasovi*
M3_S-42.03	*Anamixis* sp.	*Ampithoe tarasovi*
M3_M-43.01-02	*Anoplodactylus crassus*	*Anoplodactylus crassus* provisionally accepted
M3_S-51.01	*Anoplodactylus crassus*	Not *Anoplodactylus crassus*, possibly *Ascorhyncus*
M1_S-47.01	*Anthopleura* sp.	*Anthopleura*, probably *midori* but also very similar to *elegantissima* (low COI variation in Anthozoa)
M3_S-43.06	*Aoroides longimerus*	*Aoroides longimerus* provisionally accepted but distant from congener *Aoroides columbiae*
M3_S-43.02-06	*Aoroides longimerus*	*Aoroides longimerus* provisionally accepted but distant from congener *Aoroides columbiae*
M3_M-24.01-04	*Aoroides* sp.	*Aoroides longimerus* provisionally accepted but distant from congener *Aoroides columbiae*
M3_K-4.01	*Aplidium* sp.	*Aiptasia* sp. possibly *pulchella*
M3_K-4.02	*Aplidium* sp.	*Botrylloides leachii*
M3_K-4.03	*Aplidium* sp.	*Aplidium*, possibly *fuscum*
M3_M-51.01	*Arabella* sp.	Unknown polychaete, distant from *Arabella* Genbank records
M3_S-39.01	*Arcuatula senhousia*	*Arcuatula senhousia* confirmed (as *Musculista senhousia*)
M3_S-39.02	*Arcuatula senhousia*	*Arcuatula senhousia* confirmed (as *Musculista senhousia*)
M3_S-39.03	*Arcuatula senhousia*	*Arcuatula senhousia* confirmed (as *Musculista senhousia*)
M3_M-30.01	*Ascidia* sp.	Nemertean, probable contaminant
M3_M-35.02	*Ascidia* sp.	Nemertean, probable contaminant
M3_S-4.03	*Ascidia sydneiensis*	*Halichondria*, probable contaminant?
M3_S-4.05	*Ascidia sydneiensis*	unknown; probable contaminant
M3_S-2.01	*Ascidia zara*	*Ascidia zara* confirmed
M3_S-2.02	*Ascidia zara*	*Ciona savignyi*
M3_S-2.03	*Ascidia zara*	*Ascidia zara* confirmed
M3_K-1.07	*Balanus trigonus*	*Balanus trigonus* confirmed
M3_K-1.09	*Balanus trigonus*	*Balanus trigonus* confirmed
M3_K-1.10	*Balanus trigonus*	*Balanus trigonus* confirmed
M3_S-12.01	Botryllidae sp. 1	*Botryllus schlosseri*
M3_S-12.02	Botryllidae sp. 1	*Botryllus schlosseri*
M3_S-12.03	Botryllidae sp. 1	*Botryllus schlosseri*
M3_M-26.01	Botryllidae sp. 2	*Botrylloides violaceus*
M3_M-26.02	Botryllidae sp. 2	*Botrylloides violaceus*
M3_M-26.03	Botryllidae sp. 2	*Botrylloides violaceus*
M3_M-40.01	Botryllidae sp. 3	*Botrylloides leachii*
M3_M-40.02	Botryllidae sp. 3	*Botrylloides leachii*
M1_M-28.01	Botryllidae gen. sp. 4	*Botrylloides violaceus*

Appendix 8-2. Morphological and genetic identification of Japanese fouling community species (cont'd)

Specimen	**Morphological assignment**	**Genetic result and comments**
M1_M-28.02	Botryllidae gen. sp. 4	*Botrylloides violaceus*
M1_S-23.03	Botryllidae sp.	*Botrylloides violaceus*
M16_M-40.1	*Botrylloides violaceus*	*Botrylloides violaceus* confirmed
M16_M-40.2	*Botrylloides violaceus*	*Botrylloides violaceus* confirmed
M16_M-40.3	*Botrylloides violaceus*	*Botrylloides violaceus* confirmed
M3_M-29.01	*Botryllus schlosseri*	*Botrylloides violaceus*
M16_M-41	*Botryllus* sp.	*Botryllus schlosseri*
M3_S-52.01-03	*Brachystomia minutiovum*	*Brachystomia minutiovum* provisionally accepted; near clade of Pyramidellidae
M3_S-26.01	*Bugula neritina*	*Bugula neritina* confirmed (note cryptic species are known)
M3_S-26.02	*Bugula neritina*	*Bugula neritina* confirmed (note cryptic species are known)
M3_S-26.03	*Bugula neritina*	*Bugula neritina* confirm (note cryptic species are known)
M1_S-3.01	*Bugula stolonifera*	*Bugula stolonifera* confirmed
M1_S-3.02	*Bugula stolonifera*	*Bugula stolonifera* confirmed
M1_S-3.03	*Bugula stolonifera*	*Bugula stolonifera* confirmed
M3_M-11.01	*Caprella equilibra*	*Caprella equilibra* confirmed
M3_M-11.02	*Caprella equilibra*	*Caprella equilibra* confirmed
M3_M-11.03	*Caprella equilibra*	*Caprella equilibra* confirmed
M3_M-27.02	*Caprella mutica*	*Caprella mutica* confirmed
M3_M-27.03	*Caprella mutica*	*Caprella mutica* confirmed
M3_M-27.04	*Caprella mutica*	*Caprella mutica* confirmed
M16_MS-4.1	*Caprella penantis*	*Caprella* sp., not *penantis* cf.Genbank KC146253
M16_MS-4.2	*Caprella penantis*	*Caprella* sp., not *penantis* cf. Genbank KC146254
M16_MS-4.4	*Caprella penantis*	*Caprella* sp., not *penantis* cf. Genbank KC146255
M3_S-27.03	*Caprella scaura*	*Caprella* sp., 91% similar to *scaura*
M3_S-27.04	*Caprella scaura*	*Caprella* sp., 91% similar to *scaura*
M3_S-27.05	*Caprella scaura*	*Caprella* sp., 91% similar to *scaura*
M3_M-14.01	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M3_M-14.02	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M3_M-14.03	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M16_M-18.1	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M16_M-18.2	*Celleporina porosissima*	*Botrylloides violaceus* probable contaminant
M16_M-18.3	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M16_MS-2.2	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M16_MS-2.5	*Celleporina porosissima*	*Celleporina porosissima* provisionally accepted
M3_S-37.06	*Chlamys farreri nipponensis*	*Azumapecten farreri*
M3_S-37.07	*Chlamys farreri nipponensis*	*Azumapecten farreri*
M3_S-37.08	*Chlamys farreri nipponensis*	*Azumapecten farreri*
M3_S-80.01-02	*Chlamys* sp.	*Azumapecten farerri*
M1_K-24.01	*Chthamalus challengeri*	*Chthamalus sinensis* or *neglectus*; Genbank records ambiguous but not related to nominal *challengeri*
M3_S-1.01	*Ciona intestinalis* type A	*Ciona intestinalis* confirmed
M3_S-1.02	*Ciona intestinalis* type A	*Ciona intestinalis* confirmed
M3_S-1.03	*Ciona intestinalis* type A	*Ciona intestinalis* confirmed
M3_S-3.01	*Ciona savignyi*	*Ciona savignyi* confirmed
M3_S-3.02	*Ciona savignyi*	*Ciona savignyi* confirmed
M3_S-3.03	*Ciona savignyi*	*Ciona savignyi* confirmed
M3_K-2.01	*Cirolana harfordi japonica*	*Cirolana harfordi japonica* but *japonica* is probably a distinct species
M3_K-2.02	*Cirolana harfordi japonica*	*Cirolana harfordi japonica* but *japonica* is probably a distinct species
M3_S-77.02	*Cirolana harfordi japonica*	*Cirolana harfordi japonica* but *japonica* is probably a distinct species
M3_S-71.01	*Colomastix* sp.	*Colomastix* provisionally accepted
M3_S-71.02-06	*Colomastix* sp.	*Colomastix* sp. provisionally accepted
M3_S-30.01	*Crassostrea gigas*	*Crassostrea gigas* confirmed
M3_S-30.02	*Crassostrea gigas*	*Crassostrea gigas* confirmed
M3_S-30.03	*Crassostrea gigas*	*Crassostrea gigas* confirmed
M3_S-34.01	*Cymodoce japonica*	*Cymodoce japonica* provisionally accepted
M3_S-34.02	*Cymodoce japonica*	*Cymodoce japonica* provisionally accepted
M3_S-34.03	*Cymodoce japonica*	*Cymodoce japonica* provisionally accepted

Appendix 8-2. Morphological and genetic identification of Japanese fouling community species (cont'd)

Specimen	Morphological assignment	Genetic result and comments
M1_S-17.01	*Cypsiphimedia mala*	*Cypsiphimedia mala* provisionally accepted
M3_S-29.01	*Diadumene lineata*	*Diadumene lineata* confirmed
M3_S-29.02	*Diadumene lineata*	*Diadumene lineata* confirmed
M3_S-29.03	*Diadumene lineata*	*Diadumene lineata* confirmed
M3_S-20.02	*Didemnum* sp.	*Didemnum* sp.
M3_S-20.03	*Didemnum* sp.	*Didemnum* sp.
M3_S-20.04	*Didemnum* sp.	*Didemnum* sp.
M1_M-18.02	*Diplosoma listerianum*	*Diplosoma listerianum* confirmed
M1_M-18.03	*Diplosoma listerianum*	*Diplosoma listerianum* confirmed
M1_M-1.02	*Distaplia dubia*	*Distaplia dubia* provisionally accepted; not near *Distaplia colligans* or other Clavelinidae
M1_M-1.03	*Distaplia dubia*	*Distaplia dubia* provisionally accepted; not near *Distaplia colligans* or other Clavelinidae
M1_M-1.04	*Distaplia dubia*	*Distaplia dubia* provisionally accepted; not near *Distaplia colligans* or other Clavelinidae
M3_S-68.01	*Escharella takatukii*	*Celleporaria brunnea*, distant from *Escharella immersa*
M3_S-31.01	*Eualus leptognathus*	*Eualus leptognathus* provisionally accepted
M3_S-31.02	*Eualus leptognathus*	*Eualus leptognathus* provisionally accepted
M3_S-31.03	*Eualus leptognathus*	*Eualus leptognathus* provisionally accepted
M1_S-40.01	*Eudendrium* sp.	Hydrozoa; distant from *Eudendrium* records, closer to *Bougainvillia*
M1_S-40.02	*Eudendrium* sp.	Hydrozoa; distant from *Eudendrium* records, closer to *Bougainvillia*
M1_S-40.03	*Eudendrium* sp.	Hydrozoa; distant from *Eudendrium* records, closer to *Bougainvillia*
M3_S-9.03	*Eulalia* sp.	Hydrozoan,possible contaminant or epibiont
M3_M-32.01	*Eulalia viridis japanensis*	*Eulalia viridis* or *clavigera*
M3_M-49.01	*Fistulobalanus albicostatus*	*Fistulobalanus albicostatus* confirmed
M3_M-49.02	*Fistulobalanus albicostatus*	*Fistulobalanus albicostatus* confirmed
M3_M-49.03	*Fistulobalanus albicostatus*	*Fistulobalanus albicostatus* confirmed
M3_K-22.06	*Gammaropsis japonica*	*Gammaropsis japonica* provisionally accepted
M3_K-22.07	*Gammaropsis japonica*	*Gammaropsis japonica* provisionally accepted
M3_K-22.09	*Gammaropsis japonica*	*Gammaropsis japonica* provisionally accepted
M3_S-44.02-06	*Gitanopsis* sp.	*Gitanopsis* sp. provisionally accepted
M16_M-31	*Gordonodius zelleri*	Not *Gordonodius*; deeply contained within Leucothoe tree.
M3_M-12.01	*Halecium pusillum*	*Halecium pusillum* provisionally accepted
M3_M-12.02	*Halecium pusillum*	*Halecium pusillum* provisionally accepted
M3_M-12.03	*Halecium pusillum*	*Halecium pusillum* provisionally accepted
M3_S-22.01	*Halichondria sitiens*	*Halichondria* sp. (same as MLML sp. 1)
M3_S-22.02	*Halichondria sitiens*	*Halichondria* sp. (same as MLML sp. 1)
M3_S-22.03	*Halichondria sitiens*	*Halichondria* sp. (same as MLML sp. 1)
M3_K-35.02	*Halichondria* sp.	*Halichondria* sp. (same as "sitiens" herein)
M3_M-39.01	*Halichondria* sp.	*Halichondria* sp. (same as "sitiens" herein)
M3_M-39.02	*Halichondria* sp.	*Halichondria* sp. (same as "sitiens" herein)
M3_S-66.01	*Haliclona* sp.	*Haliclona* sp.
M3_S-40.01	*Halosydna brevisetosa*	*Halosydna brevisetosa* of China, not Canada, within Genbank
M3_S-40.02	*Halosydna brevisetosa*	*Halosydna brevisetosa* of China, not Canada, within Genbank
M3_S-62.01	*Harmothoe* sp.	*Harmothoe* provisionally accepted
M3_S-56.01	*Hemigrapsus takanoi*	*Hemigrapsus takanoi*
M3_S-56.02	*Hemigrapsus takanoi*	*Hemigrapsus takanoi*
M3_S-56.03	*Hemigrapsus takanoi*	*Hemigrapsus takanoi*
M3_S-32.02	*Heptacarpus rectirostris*	*Heptacarpus rectirostris* provisionally accepted
M3_S-32.03	*Heptacarpus rectirostris*	*Heptacarpus rectirostris* provisionally accepted
M3_S-32.04	*Heptacarpus rectirostris*	*Heptacarpus rectirostris* provisionally accepted
M3_M-2.01	*Hermilepidonotus helotypus*	*Halosydna brevisetosa* of China, not Canada, within Genbank
M16_M-16.1	*Hiatella orientalis*	*Botrylloides violaceus* probable contaminant
M16_M-16.5	*Hiatella orientalis*	*Botrylloides violaceus* probable contaminant
M3_M-9.02	*Hydroides ezoensis*	*Hydroides ezoensis* confirmed
M3_M-9.03	*Hydroides ezoensis*	*Hydroides ezoensis* confirmed
M3_M-9.04	*Hydroides ezoensis*	*Hydroides ezoensis* confirmed
M3_M-23.02-06	*Ianiropsis serricaudis*	Probably not *Ianiropsis*; it is not close to *I. epilittoralis*
M16_MS-10.3	*Jassa marmorata*	*Quasitetrastemma stimpsoni*; probable contaminant
M16_MS-10.4	*Jassa marmorata*	*Jassa* sp., not *marmorata*; cf. GU048162

Appendix 8-2. Morphological and genetic identification of Japanese fouling community species (cont'd)

Specimen	Morphological assignment	Genetic result and comments
M16_MS-10.5	*Jassa marmorata*	*Jassa* sp., not *marmorata*; cf. GU048162
M3_M-16.01	*Jassa slatteryi*	*Jassa slatteryi* confirmed
M3_M-16.02-06	*Jassa slatteryi*	*Jassa slatteryi* confirmed
M16_MS-11.1	*Jassa staudei*	*Jassa* sp., not *staudei*
M16_MS-11.2	*Jassa staudei*	*Jassa* sp., not *staudei*
M16_MS-11.3	*Jassa staudei*	*Jassa* sp., not *staudei*
M3_S-23.01	*Lepidonotus elongatus*	*Lepidonotus elongatus* provisionally accepted; cf. *Caprella* sp. 2 (Genbank KC146254)
M3_S-23.02	*Lepidonotus elongatus*	*Lepidonotus elongatus* provisionally accepted; cf. *Caprella* sp. 2 (Genbank KC146254)
M3_S-23.03	*Lepidonotus elongatus*	*Lepidonotus elongatus* provisionally accepted; cf. *Caprella* sp. 2 (Genbank KC146254)
M3_S-14.02	*Leucothoe nagatai*	*Leucothoe nagatai* provisionally accepted
M3_S-14.03	*Leucothoe nagatai*	*Leucothoe nagatai* provisionally accepted
M3_S-14.04	*Leucothoe nagatai*	*Leucothoe nagatai* provisionally accepted
M3_S-57.06-08	*Liljeborgia serrata*	*Liljeborgia serrata* provisionally accepted, closest Gammaridean in Genbank is *Cyclocaris*
M16_M-27	*Lirularia iridescens*	*Lirularia iridescens* confirmed
M3_K-44.01	*Maera pacifica*	*Maera pacifica* provisionally accepted; closest Genbank record is *M. loveni*
M3_K-44.02	*Maera pacifica*	*Maera pacifica* provisionally accepted; closest Genbank record is *M. loveni*
M3_K-44.03	*Maera pacifica*	*Maera pacifica* provisionally accepted; closest Genbank record is *M. loveni*
M3_K-44.07-06	*Maera pacifica*	*Maera pacifica* provisionally accepted; closest Genbank record is *M. loveni*
M3_S-69.01	*Maera* sp.	*Maera* sp. Closest to *M. loveni* in Genbank
M3_S-48.01	*Marphysa* sp.	*Marphysa* sp. Provisionally accepted
M3_S-48.02	*Marphysa* sp.	*Marphysa* sp. Provisionally accepted
M1_K-14.01	*Megabalanus rosa*	*Megabalanus rosa* confirmed
M1_K-14.02	*Megabalanus rosa*	*Megabalanus rosa* confirmed
M1_K-14.03	*Megabalanus rosa*	*Megabalanus rosa* confirmed
M16_M-36	*Megasyllis nipponica*	*Megasyllis nipponica*
M3_S-15.01	*Melita rylovae*	*Melita rylovae* provisionally accepted
M3_S-15.02	*Melita rylovae*	*Melita rylovae* provisionally accepted
M3_S-15.03	*Melita rylovae*	*Melita rylovae* provisionally accepted
M3_S-53.01	*Membranipora* sp. 2	*Conopeum* sp.
M3_S-25.06	*Modiolus kurilensis*	*Modiolus nipponicus* or *comptus*, not *kurilensis*
M3_S-25.08	*Modiolus kurilensis*	*Modiolus nipponicus* or *comptus*, not *kurilensis*
M3_S-25.09	*Modiolus kurilensis*	*Modiolus nipponicus* or *comptus*, not *kurilensis*
M3_S-11.03	*Molgula manhattensis*	*Molgula manhattensis* confirmed
M3_M-17.01	*Monocorophium acherusicum*	*Monocorophium acherusicum* confirmed
M3_M-17.02-05	*Monocorophium acherusicum*	*Monocorophium acherusicum* confirmed
M3_S-16.02-04	*Monocorophium uenoi*	*Monocorophium uenoi* provisionally accepted
M16_M-37	*Musculus cupreus*	*Musculus cupreus* provisionally accepted
M16_MS-18	*Musculus cupreus*	*Musculus cupreus* provisionally accepted
M3_S-38.01	*Mytilus galloprovincialis*	*Mytilus galloprovincialis* confirmed
M3_S-38.02	*Mytilus galloprovincialis*	*Mytilus galloprovincialis* confirmed
M3_S-38.03	*Mytilus galloprovincialis*	*Mytilus galloprovincialis* confirmed
M3_K-9.06	*Nemertellina yamaokai*	*Megabalanus rosa*; probable contaminant
M3_K-9.07	*Nemertellina yamaokai*	*Megabalanus rosa*; probable contaminant
M3_K-9.08	*Nemertellina yamaokai*	*Megabalanus rosa*; probable contaminant
M16_M-6.3	*Nemertellina yamaokai*	*Quasitetrastemma stimpsoni*
M16_M-6.4	*Nemertellina yamaokai*	*Quasitetrastemma stimpsoni*
M16_M-6.5	*Nemertellina yamaokai*	*Quasitetrastemma stimpsoni*
M3_S-61.01	*Nereiphylla castanea*	Undetermined; Conflicting Genbank entries
M3_S-61.02	*Nereiphylla castanea*	Undetermined; Conflicting Genbank entries
M3_S-61.03	*Nereiphylla castanea*	Undetermined; Conflicting Genbank entries
M3_S-7.06	*Nereis multignatha*	*Nereis neoneanthes*; clusters with K-56-01
M3_S-7.07	*Nereis multignatha*	*Nereis multignatha* confirmed
M3_S-7.08	*Nereis multignatha*	*Nereis multignatha* confirmed
M3_K-56.01	*Nereis neoneanthes*	*Nereis neoneanthes* provisionally accepted
M3_M-33.01	*Nereis pelagica*	*Nereis pelagica* confirmed
M3_M-33.02	*Nereis pelagica*	*Nereis multignatha*

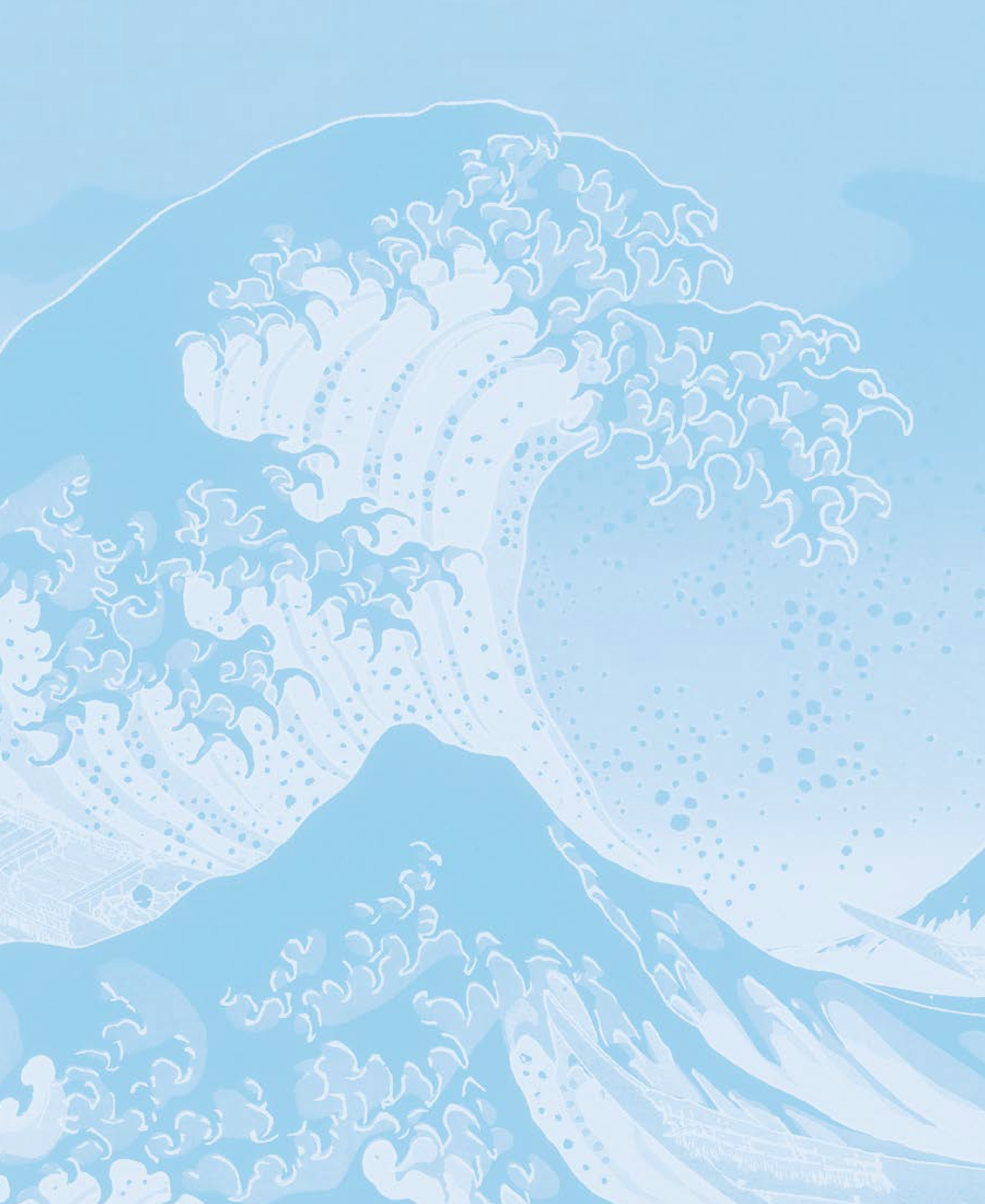
Appendix 8-2. Morphological and genetic identification of Japanese fouling community species (cont'd)

Specimen	Morphological assignment	Genetic result and comments
M3_M-33.03	*Nereis pelagica*	*Nereis pelagica* confirmed
M16_M-5.1	*Nereis vexillosa*	*Nereis* sp. not *vexillosa*
M16_M-5.2	*Nereis vexillosa*	*Nereis* sp. not *vexillosa*
M16_M-5.3	*Nereis vexillosa*	*Nereis* sp. not *vexillosa*
M3_K-31.01	*Nicolea* sp.	*Nicolea* sp. 1
M3_K-31.02	*Nicolea* sp.	*Nicolea* sp. 1
M3_K-31.03	*Nicolea* sp.	*Nicolea* sp. 2
M16_MS-1.1	*Obelia* sp.	*Obelia* possibly *geniculata*
M16_MS-1.4	*Obelia* sp.	*Botrylloides violaceus*; probable contaminant
M3_S-13.06	*Orchomene* sp.	*Orchomene* sp. provisionally accepted, closest Genbank record is *Ichnopus*
M3_S-13.07	*Orchomene* sp.	*Orchomene* sp. provisionally accepted, closest Genbank record is *Ichnopus*
M3_S-13.10	*Orchomene* sp.	*Orchomene* sp. provisionally accepted, closest Genbank record is *Ichnopus*
M16_M-33	*Pacificincola perforata*	*Pacificincola perforata* provisionally accepted
M3_S-60.01	*Paradexamine* sp.	*Paradexamine* sp. Provisionally accepted
M3_S-19.01	*Paranthura japonica*	*Paranthura* provisionally accepted
M3_S-19.03	*Paranthura japonica*	*Paranthura* provisionally accepted
M3_S-19.04	*Paranthura japonica*	*Paranthura* provisionally accepted
M3_K-23.06	*Parapleustes* sp.	*Parapleustes* sp. provisionally accepted, closest Genbank record is *Parapleustes bicuspis*
M3_K-23.07	*Parapleustes* sp.	*Parapleustes* sp. provisionally accepted, closest Genbank record is *Parapleustes bicuspis*
M3_K-23.09	*Parapleustes* sp.	*Parapleustes* sp. provisionally accepted, closest Genbank record is *Parapleustes bicuspis*
M3_K-27.01	*Perforatus perforatus*	*Perforatus perforatus* confirmed
M3_K-27.02	*Perforatus perforatus*	*Perforatus perforatus* confirmed
M3_K-27.03	*Perforatus perforatus*	*Perforatus perforatus* confirmed
M3_M-45.01	*Perophora japonica*	*Perophora japonica* confirmed
M3_M-45.02	*Perophora japonica*	*Perophora japonica* confirmed
M16_M-28.1	*Perophora* sp.	*Perophora japonica* confirmed
M3_S-6.02	*Platynereis bicanaliculata*	Nereidae; is not similar to other *Platynereis*; closest Genbank record is Nereis heterocirrata
M3_S-6.04	*Platynereis bicanaliculata*	Nereidae; is not similar to other *Platynereis*; closest Genbank record is *Nereis heterocirrata*
M3_K-24.06	*Podocerus* sp.	*Podocerus* sp. provisionally accepted
M3_M-21.01	*Polycheria* sp.	*Polycheria* provisionally accepted
M3_S-54.01	*Procephalothrix* sp.	*Cephalothrix simula*
M3_S-54.03	*Procephalothrix* sp.	*Cephalothrix simula*
M3_S-5.01	*Sabella* sp.	*Parasabella* sp.
M3_S-5.03	*Sabella* sp.	*Parasabella* sp.
M3_S-5.04	*Sabella* sp.	*Parasabella* sp.
M3_M-3.05	*Sakuraeolis* sp.	*Eubranchus*
M3_M-36.02	*Sakuraeolis* sp.	*Eubranchus*
M3_M-36.03	*Sakuraeolis* sp.	*Eubranchus*
M3_S-45.06	*Stenothoe* sp. 1	*Stenothoe* provisionally accepted
M3_S-45.07-11	*Stenothoe* sp. 1	*Stenothoe* provisionally accepted
M3_M-5.02-06	*Stenothoe* sp. 2	*Stenothoe* sp. 2; this is different from *Stenothoe* sp. 1 herein
M3_S-50.01	*Styela canopus*	*Styela*, but not *canopus* or *clava*
M3_S-50.02	*Styela canopus*	*Styela*, but not *canopus* or *clava*
M3_S-50.03	*Styela canopus*	*Styela*, but not *canopus* or *clava*
M3_M-50.01	*Styela* sp.	*Styela* not *canopus*, same as other *Styela* herein
M3_M-50.02-06	*Styela* sp.	*Styela clava*, but based on a short read
M16_M-29.1	Styelidae gen. sp.	*Botrylloides violaceus*
M16_M-29.2	Styelidae gen. sp.	*Styela clava*
M3_M-10.01	*Syllis* sp.	*Syllis vittata*
M3_M-10.02	*Syllis* sp.	*Syllis vittata*
M3_M-10.03	*Syllis* sp.	*Syllis vittata*
M3_M-47.01	*Synidotea hikigawaensis*	*Synidotea hikigawaensis* provisionally accepted
M16_MS-36.3	*Tetrastemma nigrifrons*	*Quasitetrastemma stimpsoni*
M16_MS-36.4	*Tetrastemma nigrifrons*	*Quasitetrastemma stimpsoni*
M16_MS-36.5	*Tetrastemma nigrifrons*	*Quasitetrastemma stimpsoni*
M1_S-31.01	*Theora fragilis*	*Theora fragilis* provisionally accepted

Appendix 8-2. Morphological and genetic identification of Japanese fouling community species (cont'd)

Specimen	Morphological assignment	Genetic result and comments
M3_S-35.01	*Tricellaria inopinata*	*Tricellaria occidentalis*; possible Genbank ambiguity
M3_S-35.02	*Tricellaria inopinata*	*Tricellaria occidentalis*; possible Genbank ambiguity
M3_S-35.03	*Tricellaria inopinata*	*Tricellaria occidentalis*; possible Genbank ambiguity
M3_M-31.01	*Tricellaria inopinata*	*Tricellaria occidentalis*; possible Genbank ambiguity
M3_K-50.02	*Tricellaria inopinata*	*Tricellaria occidentalis*; possible Genbank ambiguity
M16_M-45	*Vilasina decorata*	*Vilasina decorata* provisionally accepted
M3_K-18.02	*Watersipora cucullata*	*Watersipora subtorquata*, in conventional use as the globally widespread invasive
M3_K-18.03	*Watersipora cucullata*	*Watersipora subtorquata*, in conventional use as the globally widespread invasive
M3_K-18.04	*Watersipora cucullata*	*Watersipora subtorquata*, in conventional use as the globally widespread invasive
M16_MS-30	*Watersipora subatra*	*Watersipora subtorquata*, in conventional use as the globally widespread invasive
M3_M-22.01-04	*Zeuxo* sp.	*Zeuxo* sp.

M1= 1-month deployment; M3 = 3-month deployment; K = Kesennuma; M = Miyako, MS = Matsushima; S = Shiogama)



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THEME III – Rafting of Japanese Species

Chapter 9: Marine algae arriving on Japanese Tsunami Marine Debris in Oregon and Washington: The species, their characteristics and invasion potential[1]

Contributing authors: Gayle I. Hansen[1], Takeaki Hanyuda[2], and Hiroshi Kawai[2]

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Abstract

Recognizable marine debris from the Great Japan Tsunami of 2011 began arriving on the shores of Oregon and Washington in June of 2012. Many of the debris items were laden with healthy and reproductive Japanese marine algae, and there was a concern that these species might colonize and invade the Pacific coast of North America. To evaluate this risk, our study sampled, identified, and characterized the benthic marine algae arriving on tsunami debris between June 2012 and July 2016. On 42 of the most heavily fouled debris items, we identified and enumerated more than 80 species of benthic marine algae and cyanobacteria, using both morphology and DNA sequencing. The majority (55%) of these species were rare, occurring on only one to no more than three debris items, but a few (9%) were widespread, occurring on more than 12 debris items.

Many of the debris algal species had features that indicated a high colonization potential. Of the 80+ species, 85% were found to be fertile and actively releasing spores or gametes. A large percentage of these were ephemeral and/or opportunistic species capable of reproducing multiple times during a single year and of quickly colonizing new habitats. These life history features appeared to be important both in insuring the survival of the species while at sea and in assisting in their dispersal once the debris landed on shore. These features were also reflected in the global distribution of the species: 63% of the species were widespread cryptogenic forms (primarily ephemeral and opportunistic species); 6% were present on both Northeast and Northwest Pacific shores (a mixture of types) and were limited to this region; 15% were endemic to Asia (primariy annuals); and 16% were Asian species exported globally by human activities. The latter group included 3 species thought to be the most highly invasive algal species in Europe: *Undaria pinnatifida, Codium fragile* subsp. *fragile*, and *Grateloupia turuturu*.

Although the risk of colonization of Pacfic North American shores by the algae seemed high, two facts greatly lowered the risk. First, 61% of the Japanese Tsunami Marine Debris (JTMD) algal species were found to already occur along the coast (Washington to Mexico) before the tsunami, including 8 recently introduced Asian species. However, for some of these species, a genetic risk was still present since the JTMD and American populations were slightly different haplotypes (see Chapter 10). Second, although 80% of the fouled debris from the tsunami landed on the shores of Oregon and Washington indicating a particularly high invasion probability, the prompt and nearly comprehensive removal of the debris by these states appears to have been effective in eradicating most of the invasion risk. To date, no new colonization by the debris algal species has been discovered in this area.

Introduction

Collections of the algae and cyanobacteria on Japanese Tsunami Marine Debris (JTMD) began with the arrival of the Agate Beach dock (Misawa-1) in Oregon on June 5, 2012. Out on an early morning collecting trip, the first author was told of the arrival of a large debris dock (20 m long x 6 m wide x 2 m tall) on Agate Beach, near her home in Newport, Oregon. Inspecting the massive floating dock, she immediately recognized the abundant and alarming occurrence of *Undaria pinnatifida*, the most invasive macro-algal species world-wide, and numerous other Asian species. Her concern over these species led her to begin a more than 4-year study of the algae and cyanobacteria on JTMD. By enlisting the help of two algal molecular biologists in Japan who were already working with her on other projects, a well-organized collaboration was established. The first author, Hansen, obtained and enumerated the debris algal and cyanobacterial species and did the initial morphological identification and characterization of the species. Co-authors, Kawai and Hanyuda, then did the critical DNA sequencing and confirmation of the species identities. As the study progressed, the group also took on the task of collecting and mapping the JTMD algal species that were present in the Northeast Pacific before the tsunami and of surveying for new recruitment of the JTMD species along this coast. The sequencing analyses greatly facilitated this part of the study, enabling the investigators to more closely evaluate the species "shared" between both coasts: differentiating new invasions in the Northeast Pacific from earlier colonizations and determining their possible historical origins (see Chapter 10).

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[1] A more detailed account of this study with 84 species was published in *Phycologia* (2018), 57: 641-658.

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Methods

Identifying and characterizing the JTMD algal species[2]

The debris items incorporated in our study landed between Mosquito Creek, Washington and Sixes River, Oregon. In addition to our own collections, a number of state workers, volunteers, and scientists helped us to gather algal samples for the study. Comprehensive sampling of all algal species was attempted for each debris item. After collection, specimens were transported to the Hansen algal laboratory in Newport, Oregon for examination. Most often the material arrived fresh, without preservative, and the processing began immediately since the algae deteriorated rapidly. Unique species in each collection were sorted under a dissecting microscope and prepared for study. Vouchers of the species were made (via pressings and Karo-mounted microscope slides), and the material was preserved in 5% formalin/seawater (for anatomical study and photography) and silica gel (for DNA analysis).

Using the available reference literature (Yoshida, 1998; Yoshida et al., 2015; and the numerous references listed in Hansen et al., 2017a, b, c), preliminary morphological identifications were made in Oregon, and the species traits were characterized. Since many of the species mimicked one another in external appearance, the diagnostic features were most often anatomical and microscopic. Hence, for each collection, repetitive sampling and microscopic observation were necessary to assess the species. Photography was used to document the features (Hansen, 2017a, b, c). In order to determine their potential to disperse and spread along the Pacific coast of North America, the species were evaluated for fertility, longevity, and successional stage. Fertility was scored as positive if species were actively reproductive on collection; longevity was scored as either ephemeral, annual or perennial (including the pseudo-perennial forms); and successional stage was scored as either opportunistic or late successional. We also determined the frequency and survival of the the species on debris, realizing that this would help us in determing their invasion risk.

Final identifications of the species were made in Kobe, Japan, via sequencing 1–3 gene loci in each species and comparing the DNA with the sequences stored in the International Nucleotide Sequence Database Collaboration (NCBI - GenBank), the DNA Data Bank of Japan (DDBJ), and with personal data (see Chapter 10).

Determining the distribution of JTMD algal species

We used AlgaeBase[3] (Guiry and Guiry, 2017) and additional literature to determine the published global distributions of the JTMD species and the general extent of their ranges. Four global categories were used: Northeast and Northwest Pacific species (on both shores), Asian endemics, Asian species exported globally with human activities, and cryptogenic or globally widespread species (occurring in multiple oceans). To resolve local distributions, we used our own personal collection data, checklists compiled by state and national surveys, and the following public herbarium databases (all accessed in 2016): the Consortium of Pacific Northwest Herbaria, the University of British Columbia Herbarium Databases, the University of California at Berkeley and the Jepson Herbaria Specimen Portal, and the Macroalgal Herbarium Portal.

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[2] To simplify discussion in this chapter, the term "algae" will be used to include both true algae and cyanobacteria.

[3] www.algae-base.org

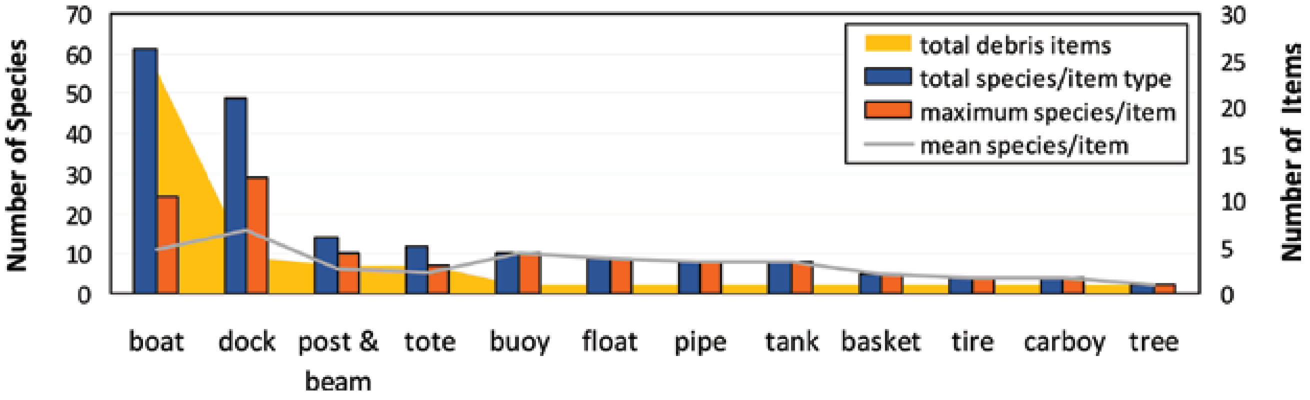

Figure 9-1. Debris types and the number of algal species present.

Results and Discussion

Debris landings along the Oregon and Washington coast

From June 2012 to July 2016, many hundreds of debris items of assorted sizes and shapes came ashore on the Oregon and Washington coasts. We selected the most heavily fouled debris items available to us (42 in total) for comprehensive assessment (Appendix 9-1). For each item, we sorted and enumerated the fouling macroalgae, and then identified and characterized the species. To avoid confusion with native debris, the debris items incorporated into our main study were only those provided with biofouling (BF) numbers (known to be JTMD items using the criteria detailed in Chapter 8). In addition, 30 plastic debris items, too small to be definitively tracked to the tsunami, were also gathered and processed by the first author for a separate study to describe the new genus and species, *Tsunamia transpacifica* (West et al., 2016; Appendix 9-2). For the current study, we tallied only the benthic algae from the 42 BF-numbered items and, on these, we identified and characterized a total of 80 macroalgal species (Appendix 9-3).

Debris types and their algal species load

The 42 BF-numbered items examined for algal species included 12 different types of debris. To determine the importance of each debris type in the transport of species, the algal species on each type were enumerated (Figure 9-1). The greatest number of species (29) was found on the Agate Beach dock, the first known debris item to arrive in Oregon. Although there were only two docks and two dock pieces sampled, they averaged 16 algal species each, the highest average of any debris type. On all four, a total of 49 species were found. Boats (and boat fragments) were, by far, the most common type of debris in the study (24), and they averaged 11 species each. In total, the boats carried 61 algal species, more than any other category of debris. Together, the docks and boats carried in 76 species or 95% of the total. The other types of debris items together (14) brought in only 34 species or 42.5% of the total. There was considerable overlap of species between the debris types, but the larger debris carried, by far, the greatest number of species.

The seasonality of the debris and its attached species

The arrival of JTMD on the Oregon and Washington coast was somewhat seasonal (Figure 9-2). Most of the debris that we sampled arrived between January and June, with very few items washing ashore between July and December. By compiling all 4 years of our study, we found that the number of debris items peaked (at 16) in March–April when 10 of the 24 debris boats and numerous other items arrived. The greatest number of algal species on debris (57) peaked slightly later, in May–June, when eight debris boats and the Agate Beach dock arrived.

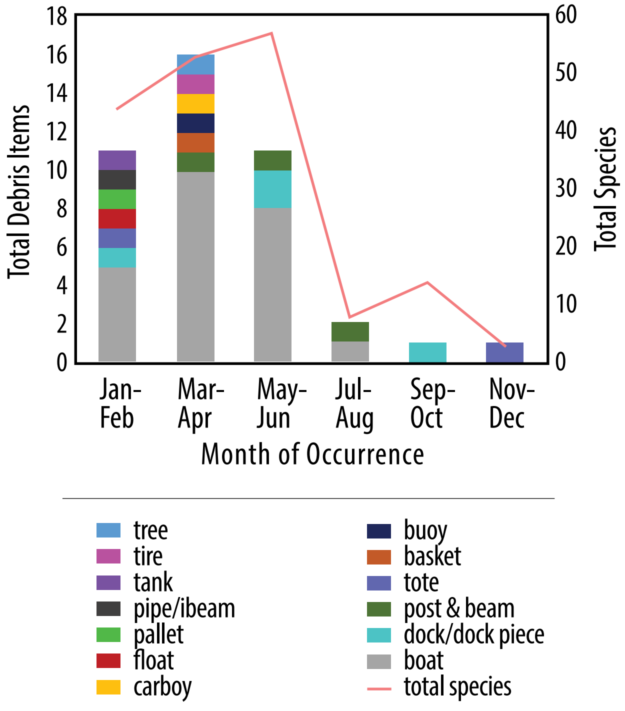

Figure 9-2. Seasonality of the debris types and their total species load from 2012–2016.

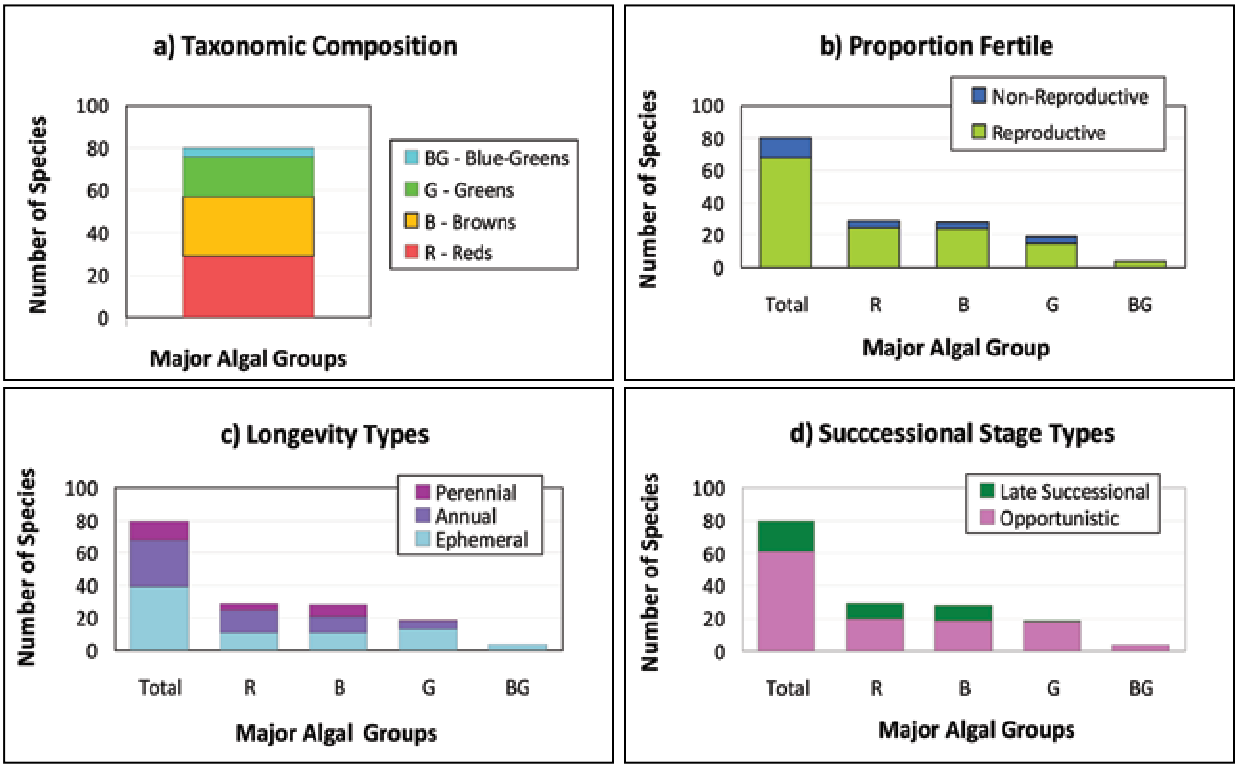

Figure 9-3. Characteristics of the marine algae found on JTMD: (a) Taxonomic composition, (b) Proportion fertile, (c) Longevity and (d) Successional stage types present.

Habitat suitability for possible colonization

In total, about 80% of the debris items with fouling biota that were officially documented to be from the Japanese tsunami came ashore on the outer coast of Oregon and Washington (Carlton et al., 2017). The potential for colonization by these hitch-hiking species seemed very clear. If fragments or propagules of the seaweeds escaped the debris and settled on shore, colonization and possible invasions could occur. To survive on shore, the algae would just need to have their basic requirements met: a hard substratum and space for attachment, appropriate submersion, adequate light, nutrients, and temperature – and limited herbivory. The area seemed prime for these species: both the Pacific coast of Tohoku and the outer coast of Oregon and Washington have rocky headlands, pocket beaches, occasional sheltered bays, and nutrient-rich water. Even the seawater temperatures along the Oregon and Washington coast (9°–11.5°C; Payne et al., 2012) are within the range of those found along the Tohoku coast of Japan (6°–22°C, Payne et al., 2012), although a requirement for the broader annual temperature range found in Japan may have prevented the survival of some species. The floristic and faunistic differences and the competition for space, too complex to consider here, also may limit colonization. Many of the debris items landed on sandy shores, remote from rock unscoured by sand. Since algal spores require a hard substratum on which to recruit, this would also prevent the survival of the propagules of some species. The maximum dispersal range of spores of the various algal species varies widely, ranging from only a few meters to many kilometers (Hoffman and Camus, 1989; Santelices, 1990). On sandy beaches without a rocky substratum nearby, the fragments and spores of species with short dispersal ranges would decay on the shore or be washed out to sea. However, the threat of colonization by many algal species was still present. It was particularly important to identify and characterize the species so that we could more closely evaluate the invasion risk and facilitate searches for new populations of JTMD algal species on the Pacific North American shore.

Characteristics of the debris species

A wide variety of algal species arrived on JTMD over the course of this study. The 80 macroalgal species identified from the debris included 36% (29) red algae, 35% (28) brown algae, 24% (19) green algae and 5% (4) bluegreen bacteria (Figure 9-3a). The proportion of red to brown algae, known as the Feldmann Index (Cormaci, 2008), is often used to evaluate the floristic affinity of samples. On JTMD, this proportion was unusually low (1.04); a ratio closer to that found in cold temperate to Arctic regions. For the Pacific coast of Japan (Titley, 2002) and the British Columbia–Oregon coast (Gabrielson et al., 2012), the Feldmann Index is reported to be 2.7. The significance of the low value on debris is not understood, but it seems likely that this ratio is not only affected by water temperature but can also be influenced by the unusual environmental conditions that occur around floating debris.

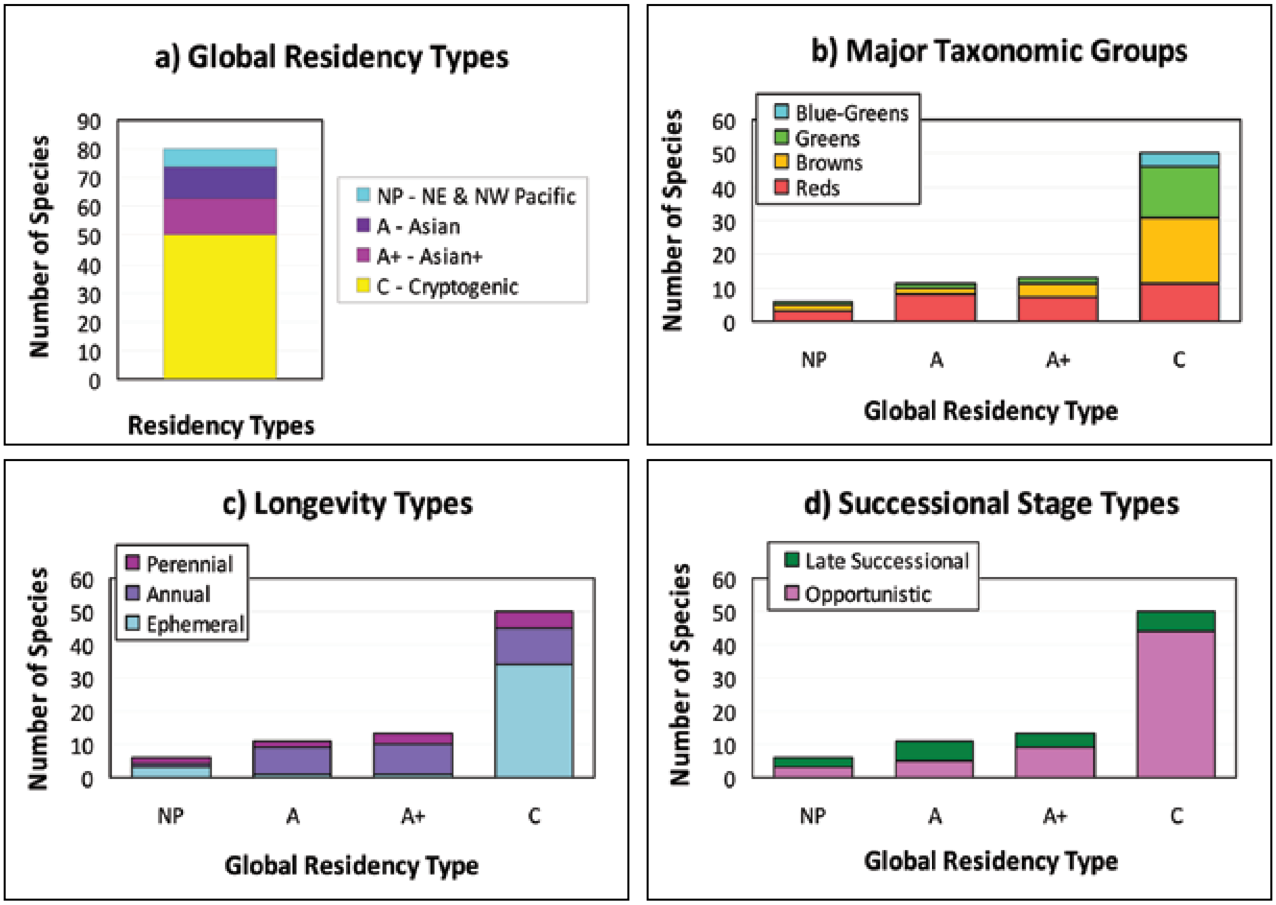

Figure 9-4. Global residency of the JTMD algal species and their characteristics: (a) Global residency types, (b) Major taxonomic groups, (c) Longevity types, and (d) Successional stage types.

For each discovered species, we characterized the life history features that we thought might lead to their dispersal and possible spread after arrival on shore. As shown in Figure 9-3, these included their reproductive state, longevity type, and successional stage in the field. A large majority of the JTMD algal species (85%, 68) were found to be actively reproductive when sampled (Figure 9-3b). Most were producing gametes or spores (e.g., *Ectocarpus, Undaria, Polysiphonia*, and *Ulva*), but some were, instead, developing asexual propagules or fragmenting (e.g., *Sphacelaria, Codium, Scytonematopsis*). The data on the longevity types (Figure 9-3c) showed that a large proportion of the species were ephemerals (49%, 39), which are short-lived species that can reproduce repeatedly and recycle themselves throughout the year whenever the conditions are appropriate. A moderate number were annuals (36%, 29), species that last for up to 1 year, and only a few (15%, 12) were perennials or pseudo-perennials, species that live for more than 1 year. A tabulation of the successional stage types (Figure 9-3d) revealed that late successional forms were a relatively minor component of the debris flora, comprising only 24% (19) of the species. The opportunistic species, well-known for their ability to quickly colonize barren areas, were far more abundant, and comprised 76% (61) of the debris species.

The global occurrence of the debris species

The four categories of global distribution included in Figure 9-4 are: "NP" (North Pacific) for species known mainly from both sides of the North Pacific (with rare occurrences in Alaska and the South Pacific); "A" (Asian-only) for species endemic to Asia from Russia to the Philippines; "A+" (Asian global invaders) for species originating in Asia that have been distributed globally by human activities; and "C" (Cryptogenic) for globally widespread species (from multiple oceans) considered to have unknown origins (Carlton, 1996).

Using these categories, the world-wide distributions of the algal species found on JTMD were assessed. The North Pacific group composed only 7% (6) of the species; these were a combination of red and brown algae and a mixture of life history forms. The Asian-only species were 14% (11) of the total; these were primarily red algae and annual forms. The limited ranges of these species appears to be influenced in part by their life history type and/or spore dispersal method. Species in the other two categories were globally widespread. The Asian+ species were 16% (13) of the total species on JTMD;

Table 9-1. The Asian+ species on JTMD and their occurrence in Washington, Oregon, California, and Mexico.

Algae group	Name	Pacific North America records
Brown	*Mutimo cylindricus*	California, Mexico
Brown	*Saccharina japonica*	Not detected
Brown	*Planosiphon gracilis*	Mexico
Brown	*Undaria pinnatifida*	California, Mexico
Green	*Codium fragile* subsp. *fragile*	California, Washington
Red	*Ulva australis*	California, Oregon, Washington
Red	*Antithamnion nipponicum*	California, Mexico
Red	*Ceramium sugminbooi*	California, Oregon, Washington
Red	*Chondrus giganteus* f. *flabellatus*	Not detected
Red	*Grateloupia turuturu*	California, Mexico
Red	*Neosiphonia japonica*	Not detected
Red	*Polysiphonia morrowii*	Not detected
Red	*Pyropia yezoensis*	Not detected

69% (9) of these were annuals. Eight have already been introduced into California and/or Mexico (Miller et al., 2011; Hughey and Boo, 2016), and three have recently been found in Oregon and/or Washington (Table 9-1). These species, with distributions documented through sequencing, are thought to have been transported globally with aquacultured species, and a number are considered hazardous invaders (Nyberg and Wallentinus, 2005). By far, the largest number of species on JTMD were cryptogenic. The 50 species (63%) in this category were dominated by ephemeral (68%) and/or opportunistic species (88%), including all the blue-greens and most of the green algae. These highly reproductive groups are often found in hull fouling, a fact that has increased their distribution globally (Mineur et al., 2012). Their occurrence on tsunami debris is significant in that it will further assist in their spread.

Frequency of occurrence on the 42 debris items

The frequency of occurrence of the individual species on debris would also provide information on their invasion threat. By tallying the occurrence of unique species on our 42 debris items, (Figure 9-5), we found that the majority of the species (55% or 44) occurred on only 1 to 3 debris items. The sporadic occurrence of new species on debris was not uncommon throughout our study, further increasing the number of rare species. We found only 6 species that occurred on more than 15 debris items. *Petalonia fascia* and *Feldmannia mitchelliae* were the most frequent (each occurring on 24 debris items). Other frequent species were *Ectocarpus siliculosus* var. *pygmaeus* (on 22 items), *Ulva compressa* and *Colaconema daviesii* (both on 20 debris items), and *Ulva linza* (on 17 items). These most widespread species were all cryptogenic and opportunistic, and all, except *Petalonia*, were ephemerals.

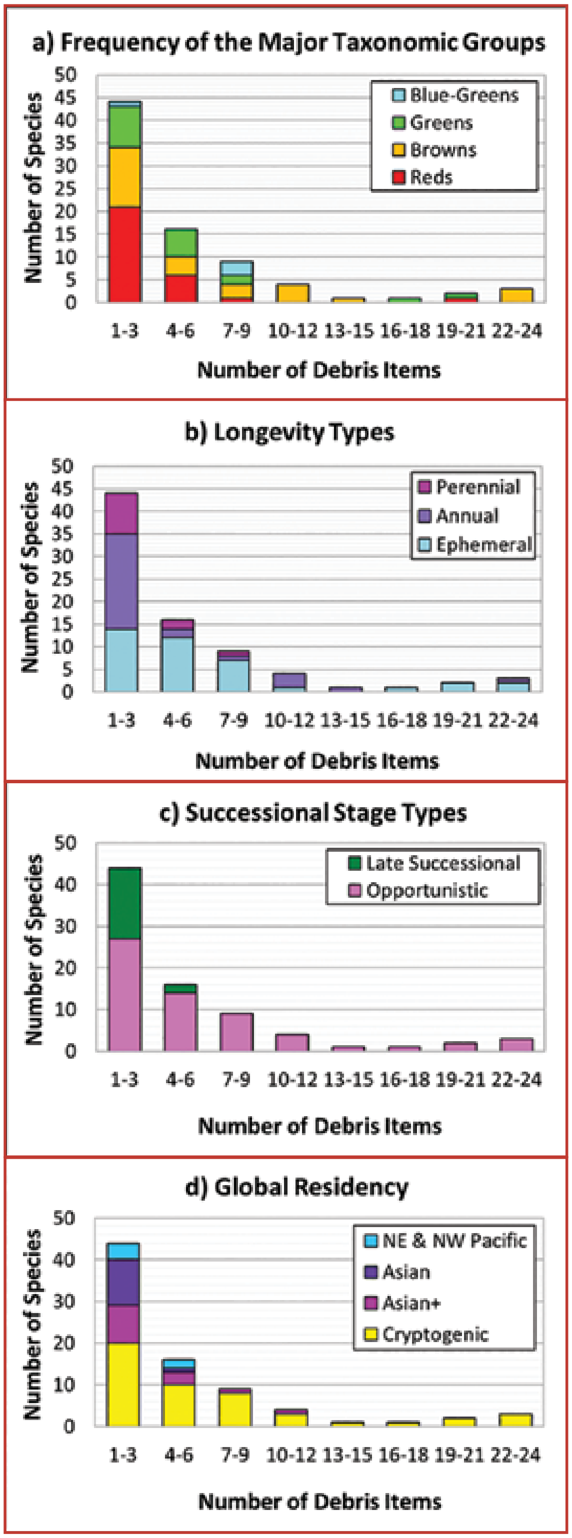

Figure 9-5. Frequency of occurrence of species on the JTMD items. The items are grouped in sets of 3 and the graphs are coded for the major taxonomic groups, longevity and successional stage types, and global residency of the species.

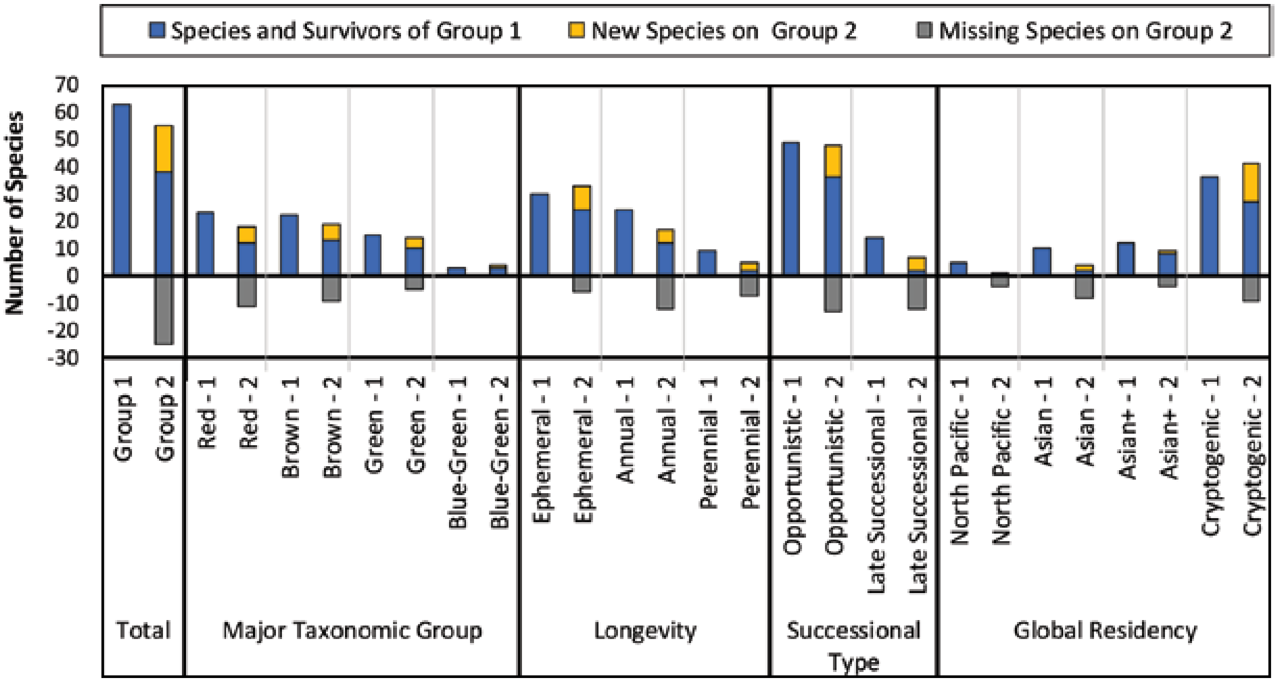

Figure 9-6. Algal species survival on JTMD. Species present on debris items found during the first half of the study (Group 1, items 1–21, June 2012 to April 2014) vs. their occurrence or absence on debris items found during the second half of the study (Group 2, items 22–42, May 2014 to July 2016).

Survival of the debris algal species

The algal species reaching the Pacific shores of North America during this study survived at sea for a minimum of 15 months (Agate Beach dock of June 2012) and some survived for more than 5 years (Falcon Cove Boat of July 2016). For the surviving species, each must have had its basic requirements met during the journey as described earlier: suitable substrate, submergence, light, temperature, and nutrients. However, an unknown proportion of species did not survive the journey, either as a result of stresses at sea or due to the variable life history features of the species, or both. By comparing the species occurrences at different times throughout our study, we were able to obtain some information on the probable survival of the species while at sea.

Some of our observations could be explained through a basic knowledge of the species. *Saccharina japonica*, the largest kelp found on JTMD, is a biennial, living only 2 years. On the Agate Beach dock (1 year after the tsunami), it was very abundant, the blades were 1 to 1.5 m long, and it appeared to be 1 to 2 years old. By the second year (2 years after the tsunami), no large thalli and only a few small blades were present, likely the first-year progeny that had seeded at sea. After that, no further *Saccharina* thalli were observed. Many of the other kelps and large algae were annuals: these survived only until our first year of observation and were not seen later, suggesting that they did not recycle their populations while at sea.

We also set up a proxy survival investigation of the algal species at sea by comparing the species found on debris during the first half of the study with those found on debris during the last half of the study (Figure 9-6). During this 4-year investigation, we found that the final change in species numbers was due both to species being lost and new species being gained. The gained species were added to our surviving species since they were species that had survived on debris that was initially unavailable for observation. The lost species were those no longer found after the first half of our study, and these were the most revealing.

Based on this study, the most successful survivors at sea were the opportunistic and ephemeral forms (and the linked cryptogenic forms). The lifespan of the species in these categories is relatively short, so to survive on JTMD, the species had to recycle themselves through sexual or asexual reproduction many times each year and then recolonize the debris, and often their recolonization was in greater abundance than before. These species were nearly always fertile and were often widespread on our debris collections. It seemed evident that when a disturbance created barren areas on debris at sea, these species were ready to colonize. With no competitive input from outside species, their numbers gradually increased. Their frequent reproduction has made them well-suited for long-term survival on debris, and well-equipped for quickly colonizing the new habitats that they might encounter when their debris comes ashore.

Other factors appeared to further increase the fertility of the JTMD species as they approached shore. Parts of the central Pacific Ocean are known to be oligotrophic or low in nutrients. This is particularly true for areas south of the North Pacific Current where some JTMD may have traveled. Along the Oregon and Washington coast, the

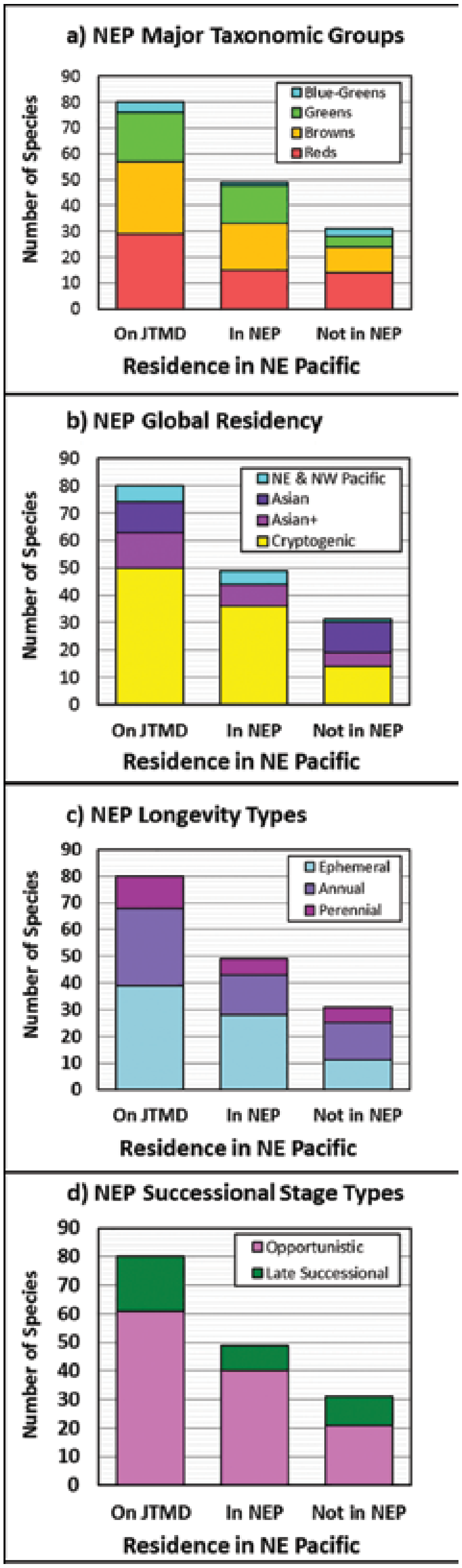

Figure 9-7. The JTMD algal species present or absent in the Northeast Pacific before the tsunami and their characteristics. NE = Northeast, NW = Northwest, NEP = Northeast Pacific (only Washington to Mexico).

nearshore areas are nutrient-rich due to heavy rainfall causing runoff from the land and to spring–summer upwelling. Upwelling in this region also causes the nearshore water to be lower in temperature than the open ocean areas. Both of these features, higher nutrients and cooler temperatures, are known to enhance reproduction in some species (Lobban and Harrison, 1994). Greater propagule production would further increase the ability of the species to disperse off the debris and onto the shore.

The presence of JTMD algal species in the Northeast Pacific before the tsunami

Colonization of the Northeast Pacific by species from JTMD seemed to be inevitable. However, one factor greatly reduced this risk. After carefully examining the existing literature and the prior herbarium records, we discovered that 61% (49) of the JTMD species were already present in the Northeast Pacific (Washington to Mexico) before the tsunami. To more closely examine this, we compared the proportions of the species only on debris with those already present in the Northeast Pacific (Pacific North America) (Figure 9-7). As we expected, a high percentage of the forms that we know to be highly reproductive were already present: 79% of the green algae (Figure 9-7a), including the widespread and often reproductive *Ulva* species, 72% of the ephemerals (Figure 9-7c), and 66% of the opportunistic species (Figure 9-7d). In addition, 8 of the well-known A+ global invaders were already present (Figure 9-7d, Table 9-1). However, 39% (31) of the 80 species were still found only to occur on debris, including 5 of the 13 A+ species and some members of all of the featured groups that we had investigated (unless excluded by definition) (see Appendix 9-4) – so the invasion risk was still very high.

Conspecific species mapping and the search for new invasions

As a part of our study, we mapped the areas in the Northeast Pacific where populations of species conspecific with those on JTMD already occurred (Appendix 9-5). We discovered that the highest species numbers occurred in sheltered bays. Due to habitat suitability, we suspected that these areas where JTMD populations already existed were the most likely locations for new invasions to take place. We established survey sites in five of these areas with a known history of JTMD species occurrence and a proximity to known debris landings. The sites were: Grays Harbor, Willapa Bay, Ilwaco, Nehalem River, and Yaquina Bay. We sampled these sites over a 2-year period. Similar sites in British Columbia and Alaska were also sampled in a related study by Kawai, Hansen and Lindstrom (Chapter 14). In each area, we collected and sequenced the North American populations of species conspecific with those on JTMD and then compared these sequences with those of the identical species on JTMD and in Japan. Sequencing was particularly important since it could enable us to differentiate any new invasions from the existing populations. It also allowed us to determine the relatedness of many of our "shared species" and to learn something about the history of colonization (see Chapters 10 and 14).

Throughout our 2-year conspecific (with JTMD species) survey , we found no species introductions that could be documented by sequencing to be from JTMD. However, we did discover that the haplotypes of more than 10 of our "shared" species were not truly identical with those on JTMD (Hansen et al., 2017a, b, c; Hanyuda et al., 2018). The introduction of these species into the Northeast Pacific from JTMD would still be an invasion risk, i.e., a genetic risk, since these species could hybridize with the populations already here. The haplotype variants included 3 of the A+ globally invasive species previously introduced into California or Mexico (*Mutimo cylindricus, Undaria pinnatifida* and *Grateloupia turuturu*). In addition, several of the haplotype variants of our "shared" species were found to be most similar to populations outside of Asia, some even to the Atlantic – indicating that these populations had been exchanged or introduced from areas other than Asia.

The invasion risk and the effective management solution

Although thousands of debris items are known to have come ashore in Pacific North America and Hawaii from the Great Japan Tsunami of 2011 (Clarke Murray et al., 2018), only a small portion of these items could be verified as coming from the Japanese tsunami, and even fewer were checked for the occurrence of fouling biota. Much of this was due to the remote locations of the debris landings, particularly in British Columbia and Alaska. However, there was a major effort to comprehensively gather and examine any debris items with biofouling that landed in the more accessible regions. Carlton et al. (2017) accessed, sampled, and verified the tsunami origin of 634 biofouled debris items that arrived in Pacific North America, Hawaii, and Midway Atoll during his close to 5-year JTMD study. By tallying the BF (biofouling) debris inventory from this study, we found that 80% of the recorded biofouled items arrived on the outer coast of Washington or Oregon, the area apparently most heavily impacted by the debris – and also the focus of our study. With the debris in our investigation carrying so many reproductive algal species and hazardous global invaders, the risk of invasion in this area could have been extraordinarily high.

However, shortly after the first debris items bearing invasive species came ashore, the state agencies in Oregon and Washington devised a management plan to prevent most of the invasion catastrophy: they would remove the contaminating debris from the beaches as soon as possible after landing – thus removing the contaminating species and all except the initially released fragments and propagules. The plan went into action in June of 2012, shortly after the arrival of the first large debris item, the Agate Beach dock. Subsidized by the Ministry of the Environment in Japan, the state agencies in Oregon and Washington and numerous volunteers began a massive effort to remove the fouled debris from the beaches. Steve Rumrill (Oregon Department of Fish and Wildlife, pers. comm.) stated that "90% of the larger debris items (the boats and docks) were removed from the beaches within 24 hours of their arrival". A similar removal effort occurred in Washington (Allen Pleus, pers. comm.). In both areas, numerous individuals and volunteer groups (including Surfriders, SOLVE, and CoastWatch) also took part in the cleanup. These groups combed the accessible beaches and removed and discarded nearly all the smaller debris items. The effort was so thorough that it was often difficult to find enough fouled debris to conduct our studies.

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Since no new populations of algae from tsunami debris have yet been found in either Oregon or Washington, it appears that the prompt and nearly comprehensive cleanup efforts in these two states have been effective in preventing most of the potential invasion disaster. However, we are still vigilent for new colonization of JTMD species, particularly in the less accessible areas along the coast. With the new guides that we have created for the species (Hansen et al., 2017a, b, c; Kawai et al., 2017) and the sequences to the species deposited in the DNA Databank of Japan, we are now well-equipped to recognize the species if they do appear.

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Chapter 9 Appendices

Appendix 9-1. Japanese Tsunami Marine Debris items collected from the coasts of Oregon and Washington for the algal study

Appendix 9-2. Plastic debris collected from the coasts of Oregon and Washington for a study of Stylonematophyceae crusts (West et al., 2016)

Appendix 9-3. Marine algae identified from JTMD arriving in Oregon and Washington from June 2012 to July 2016

Appendix 9-4. JTMD algal species not yet present in Pacific North America (Washington to Mexico) and their global residency

Appendix 9-5. Map of the known JTMD Algal species occurring along the outer coast of Washington and Oregon before the tsunami

Appendix 9-1. Japanese Tsunami Marine Debris items collected from the coasts of Oregon and Washington for the algal study[1]

#	BF #	State	Site name - (Hansen additions)	Item	Collection date	Year	Species count
1	BF-1	OR	Agate Beach	dock	June 5	2012	29
2	BF-2	WA	Ilwaco (Benson Beach)	boat	June 15	2012	10
3	BF-8	WA	Mosquito Creek	dock	Jan 5	2013	16
4	BF-293	WA	Long Beach (Seaview rusty)	Pipe/I-beam	Jan 28	2013	9
5	BF-23	OR	Gleneden Beach	boat	Feb 6	2013	9
6	BF-234	OR	South Beach	tank	Feb 9	2013	7
7	BF-28	OR	Horsfall Beach	boat	Feb 21	2013	15
8	BF-235	WA	Long Beach	tire	Mar 1	2013	4
9	BF-36	OR	Florence (Muriel Ponsler)	boat	Mar 14	2013	8
10	BF-39	OR	Cannon Beach (S-Jockey Cap)	boat	Mar 22	2013	8
11	BF-40	WA	Long Beach	fish boat	Mar 22	2013	8
12	BF-50	OR	Coos Bay Spit	boat	Apr 22	2013	3
13	BF-58	OR	Clatsop Beach	boat	May 30	2013	10
14	BF-59/61	OR	Nye Beach	post & beam	May 30	2013	10
15	BF-108	OR	Cape Arago (Lighthouse Beach)	post & beam	July 11	2013	2
16	BF-130	OR	Clatsop Beach	dock piece	Oct 9	2013	15
17	BF-134	WA	Twin Harbors State Park	boat	Jan 17	2014	11
18	BF-135	OR	Yachats (fiberglass fragment)	boat	Feb 18	2014	19
19	BF-331	WA	Oysterville	boat	Mar 14	2014	9
21	BF-171	OR	Tillamook Bay spit	post & beam	Apr 25	2014	7
20	BF-160	OR	Tillamook Bay spit	tree	Apr 26	2014	2
22	BF-173	OR	South Beach (Lost Creek black)	buoy	Apr 27	2014	10
23	BF-188?	OR	Cape Lookout Beach #1	boat	May 3	2014	4
24	BF-196	OR	Waldport	boat	May 12	2014	8
25	BF-208	OR	Cape Arago (North Cove)	boat	May 19	2014	14
26	BF-223/224	WA	Long Beach (Ilwaco)	boats 2	May 29	2014	9
27	BF-227/228	WA	Long Beach	boats 2	Jun 5	2014	7
28	BF-277	OR	Seal Rock	tote	Nov 30	2014	3
29	BF-285	WA	Long Beach (Styrofoam fragment)	boat	Jan 4	2015	5
30	BF-462	WA	Long Beach (black)	float	Jan 4	2015	8
31	BF-288	OR	Beverly Beach	pallet	Jan 20	2015	7
32	BF-461	OR	Manzanita (blue)	baskets	Mar 2	2015	5
33	BF-356	OR	In ocean-Seal Rock	boat	Apr 10	2015	16
34	BF-397	WA	Long Beach	dock piece	May 1	2015	3
35	BF-402	WA	Long Beach (Seaview)	boat	May 12	2015	17
36	BF-500	WA	Long Beach (red)	tote	Feb 16	2016	6
37	BF-526	OR	Horsfal Beach 2	boat	Mar 22	2016	24
38	BF-656	OR	Quail Street (plastic)	carbuoy	Mar 26	2016	4
39	BF-545	OR	Umqua River mouth	boat	Mar 26	2016	6
40	BF-533	OR	Roads End	boat	Mar 28	2016	24
41	BF-538	OR	Sixes River mouth	boat	Apr 16	2016	17
42	BF-652	OR	Falcon Cove beach	boat	Jul 26	2016	6

[1] Items are arranged by collection date; BF # = biofouling number.

Appendix 9-2. Plastic debris collected from the coasts of Oregon and Washington for a study of Stylonematophyceae crusts (West et al., 2016)[1]

GIH[2] #	State	Site	Plastic debris object	Collection date	Year	Collector
130	WA	Long Beach	White tray fragment	Mar 2	2015	Lewis
416[3]	WA	Long Beach	White bottle	Nov 5	2015	Lewis
630	OR	Hubbard Creek Beach	White tray fragment	Nov 25	2015	Treneman
422	OR	Beverly Beach	Black buoy	Dec 17	2015	Sarver
426	OR	Otter Crest	Light blue basket	Dec 20	2015	Sarver
430	OR	Nye Beach	Pink float fragment	Dec 26	2015	Sarver
431	OR	Nye Beach	Yellow basket	Dec 26	2015	Sarver
432	OR	Nye Beach	White box fragment	Dec 26	2015	Sarver
433	WA	Long Beach dumpster	White tray & basket fragments	Jan 9	2016	Barton
434	WA	Long Beach dumpster	Black buoy	Jan 9	2016	Barton
435	WA	Long Beach dumpster	Black basket fragment	Jan 9	2016	Barton
485	WA	Leadbetter Point	Black buoy	Feb 9	2016	Lewis
490	WA	Leadbetter Point	White jug-Clover Chemical	Feb 9	2016	Lewis
494	WA	Leadbetter Point	White float	Feb 9	2016	Lewis
478	WA	Leadbetter Point	Red beer tote-Japanese writing	Feb 19	2016	Lewis
496	WA	Grayland Beach	White jug-Clover Chemical	Mar 5	2016	Hansen
610	OR	Nye Beach	White float fragment	Mar 18	2016	Hansen
611	OR	Nye Beach	White broken basket	Mar 18	2016	Hansen
612	OR	Lost Creek N.	White tray fragment	Mar 18	2016	Hansen
613	OR	Lost Creek N.	White tubular fragment	Mar 18	2016	Hansen
614	OR	Lost Creek N.	White tray fragment	Mar 18	2016	Hansen
615	OR	Lost Creek N.	White tray fragment	Mar 18	2016	Hansen
622	OR	Quail Street Beach	White jug-Nissan Chemicals	Mar 24	2016	Custer
616	OR	Yaquina Bay Lighthouse Beach	Blue basket fragment	Mar 26	2016	Hansen
617	OR	Yaquina Bay Lighthouse Beach	White tray fragment	Mar 26	2016	Hansen
618	OR	Yaquina Bay Lighthouse Beach	Black broken grid	Mar 26	2016	Hansen
619	OR	Otter Crest Beach	Blue basket fragment	Mar 26	2016	Hansen
620	OR	Otter Crest Beach	White plastic disc	Mar 26	2016	Hansen
621	OR	Nye Beach	White tray fragment	Mar 26	2016	Hansen
623	OR	Quail Street Beach	White bucket-Miyabe writing	Mar 26	2016	Custer

[1] Items are arranged by collection date.

[2] GIH #= the collection number of Gayle Hansen.

[3] This sample is the debris item from which the type culture for *Tsunamia transpacifica* (JAW-4874) was derived.

Appendix 9-3. Marine algae identified from JTMD arriving in Oregon and Washington from June 2012 to July 2016

Group	Species name[1,2]	Additional verification[3]
B	*Alaria crassifolia* Kjellman *in* Kjellman *et* Petersen	s
B	*Analipus japonicus* (Harvey) M.J. Wynne	s
B	*Costaria costata* (C. Agardh) De A. Saunders	s
B	*Desmarestia japonica* H. Kawai *et al.* in Yang *et al.*	s
B	*Desmarestia viridis* (O.F. Müller) J.V. Lamouroux	
B	*Ectocarpus acutus* Setchell *et* N.L. Gardner	s
B	*Ectocarpus arctus* Kützing	ss
B	*Ectocarpus crouaniorum* Thuret *in* Le Jolis	s
B	*Ectocarpus* cf. *penicillatus* (C. Agardh) Kjellman	ss
B	*Ectocarpus siliculosus* var. *pygmaeus* (Areschoug) Gallardo cpx.	ss
B	*Feldmannia irregularis* (Kützing) G. Hamel	ss
B	*Feldmannia mitchelliae* (Harvey) H.-S. Kim	s
B	*Hincksia granulosa* P.C. Silva *in* Silva, Meñez *et* Moe	
B	*Hincksia sandriana* (Zanardini) P.C. Silva *in* Silva, Meñez *et* Moe	
B	*Kuckuckia spinosa* (Kützing) Kornmann *in* Kuckuck cpx.	ss
B	*Mutimo cylindricus* (Okamura) Kawai *et* Kitayama	s
B	*Petalonia fascia* (O.F. Müller) Kuntze cpx.	s
B	*Petroderma maculiforme* (Wollny) Kuckuck	s
B	*Planosiphonia gracilis* (Kogame) McDevit *et* G.W. Saunders[1]	s
B	*Planosiphonia zosterifolius* (Reinke) McDevit *et* G.W. Saunders[1]	s
B	*Protectocarpus speciosus* (Børgesen) Kornmann *in* Kuckuck	
B	*Pseudolithoderma paradoxum* Sears *et* Wilce cpx.	#
B	*Punctaria latifolia* Greville cpx.	s
B	*Saccharina japonica* (Areschoug) C.E. Lane, C. Mayes, Druehl *et* G.W. Saunders	s
B	*Scytosiphon lomentaria* (Lyngbye) Link cpx.	s
B	*Sphacelaria rigidula* Kützing	s, #
B	*Sphacelaria solitaria* (Pringsheim) Kylin	
B	*Undaria pinnatifida* (Harvey) Suringar	s
G	*Blastophysa rhizopus* Reinke	#
G	*Blidingia minima* var. *minima* (Nägeli *ex* Kützing) Kylin	s
G	*Blidingia subsalsa* (Kjellman) Kornmann *et* Sahling	s
G	*Bryopsis plumosa* (Hudson) C. Agardh cpx.	s
G	*Bryopsis stolonifera* W.J. Lee, S.M. Boo *et* I.K. Lee	
G	*Cladophora albida* (Nees) Kutzing	s, #
G	*Cladophora vagabunda* (Linnaeus) Hoek cpx.	s, #
G	*Codium fragile* subsp. *fragile* (Suringar) Hariot	s
G	*Entocladia polysiphoniae* Setchell et Gardner	
G	*Epicladia flustrae* Reinke cpx.	#
G	*Halochlorococcum moorei* (N.L. Gardner) Kornmann *et* Sahling	
G	*Ulothrix implexa* (Kützing) Kützing	
G	*Ulva australis* Areschoug	s
G	*Ulva compressa* Linnaeus	s
G	*Ulva intestinalis* Linnaeus cpx.	ss
G	*Ulva lactuca* Linnaeus	s
G	*Ulva linza* Linnaeus	ss
G	*Ulva prolifera* O.F. Müller	s
G	*Ulva simplex* (K.L. Vinogradova) H.S. Hayden *et al. sensu* Ogawa[1]	ss
R	*Acrochaetium microscopicum* (Nägeli *ex* Kützing) Nägeli *in* Nägeli *et* Cramer	
R	*Acrochaetium pacificum* Kylin	
R	*Antithamnion nipponicum* Yamada *et* Inagaki	#
R	*Bangia* cf. *fuscopurpurea* (Dillwyn) Lyngbye	ss
R	*Ceramium sungminbooi* J. Hughey *et* G. Boo	s
R	*Chondrus giganteus* f. *flabellatus* Mikami	s
R	*Chondrus yendoi* Yamada *et* Mikami *in* Mikami	s
R	*Colaconema daviesii* (Dillwyn) Stegenga cpx.	ss
R	*Colaconema savianum* (Meneghini) Nielsen cpx.	ss
	Devaleraea mollis (Setchell *et* N.L. Gardner) G.W. Saunders *et al.* cpx.[1]	ss
R	*Erythrocladia irregularis* Rosenvinge	
R	*Erythrotrichia carnea* (Dillwyn) J. Agardh	
R	*Erythrotrichia incrassata* T. Tanaka	
R	*Grateloupia livida* (Harvey) Yamada	s
R	*Grateloupia turuturu* Yamada	s
R	*Leptofauchea leptophylla* (Segawa) M. Suzuki *et al.*	#
R	*Meiodiscus spetsbergensis* (Kjellman) G.W. Saunders *et* J. McLachlan	
R	*Melanothamnus japonicus* (Harvey) Diaz-Tapia *et* Maggs	
R	*Melanothamnus yendoi* (Segi) Diaz-Tapia *et* Maggs	#
R	*Neodilsea yendoana* Tokida	s
R	*Polysiphonia koreana* D. Bustamante, B.Y. Won *et* T.O. Cho	ss, #
R	*Polysiphonia morrowii* Harvey	s
R	*Polysiphonia villum* J. Agardh	s
R	*Porphyrostromium japonicum* (Tokida) Kikuchi *in* Kikuchi *et* Shin	
R	*Ptilota serrata* Kützing	#
R	*Pyropia pseudolinearis* (Ueda) N. Kikuchi, M. Miyata, M.S. Hwang *et* H.G. Choi cpx.	ss
R	*Pyropia yezoensis* (Ueda) M.S. Hwang *et* H.G. Choi *in* Sutherland *et al.*	s
R	*Schizymenia dubyi* (Chauvin *ex* Duby) J. Agardh	s
R	*Tsunamia transpacifica* J. West, G. Hansen, T. Hanyuda *et* G. Zuccarello cpx.	s
BG	*Calothrix scopulorum* C. Agardh *ex* Bornet *et* Flahault cpx.	#
BG	*Chroococcus submarinus* (Hansgirg) Kovácik	#
BG	*Lyngbya confervoides* C. Agardh *ex* Gomont	#
BG	*Scytonematopsis crustacea* (Thuret) Koválik *et* Komárek cpx.	#

B = brown algae (Ochrophyta), BG = bluegreen bacteria (Cyanobacteria), G = green algae (Chlorphyta), R = red algae (Rhodophyta), cpx. = a complex of closely related unnamed haplotypes that are still retained in the same species, s = sequenced, ss = sequenced but requiring further study, # = verified by a monographic expert.

[1] Name changes in the checklist since the project ended:
(1) *Planosiphon gracilis* (Kogame) McDevit and G.W. Saunders (2017) replaced *Scytosiphon gracilis*
(2) *Planosiphon zosterifolius* (Reinke) McDevit and G.W. Saunders (2017) replaced *Petalonia zosterifolia*.
(3) *Devaleraea mollis* (Setchell and Gardner) G.W. Saunders, C.L. Jackson and Salomaki (2017, '2018') replaced *Palmaria mollis*. We use *Devaleraea mollis* complex because the sequences of the Japanese and American populations of this species differ, and the names have not yet been fully resolved.
(4) The synonymy of *Ulva simplex sensu* Ogawa with *U. prolifera* has been proposed by Cui et al. (2018), but we retain the Japanese name until further study can be completed.

[2] Four additional species were discovered in material from the 42 debris items after the project ended: (1) *Hecatonema streblonematoides* (Setchell et N.L. Gardner) Loiseaux; (2) *Hincksia ovata* (Kjellman) P.C. Silva in Silva Meñez et Moe; (3) *Acrosiphonia arcta* (Dillwyn) Gain; (4) *Bolbocoleon piliferum* Pringsheim. Although not included in our current tables, these are listed in Hansen et al. (2017a, b, c; 2018).

[3] After preliminary morphological identification, these verification methods were used to confirm and correct the species identifications.

Appendix 9-4. JTMD algal species not yet present in Pacific North America (Washington to Mexico) and their global residency

Group	Species name	Global residency
B	*Alaria crassifolia*	A
B	*Desmarestia japonica*	A
B	*Ectocarpus crouaniorum*	C
B	*Ectocarpus* cf. *penicillatus*	C
B	*Kuckuckia spinosa* cpx.	C
B	*Planosiphonia zosterifolius*	C
B	*Protectocarpus speciosus*	C
B	*Pseudolithoderma paradoxum* cpx.	C
B	*Saccharina japonica*	A+
B	*Sphacelaria solitaria*	C
G	*Blastophysa rhizopus*	C
G	*Bryopsis stolonifera*	A
G	*Epicladia flustrae* cpx.	C
G	*Ulva simplex sensu* Ogawa	C
R	*Chondrus giganteus* f. *flabellatus*	A+
R	*Chondrus yendoi*	A
R	*Erythrotrichia incrassata*	A
R	*Grateloupia livida*	A
R	*Leptofauchea leptophylla*	A
R	*Melanothamnus japonicus*	A+
R	*Melanothamnus yendoi*	A
R	*Neodilsea yendoana*	A
R	*Polysiphonia koreana*	A
R	*Polysiphonia morrowii*	A+
R	*Porphyrostromium japonicum*	A
R	*Pyropia pseudolinearis* cpx.	A
R	*Pyropia yezoensis*	A+
R	*Tsunamia transpacifica* cpx.[1]	NP/C
BG	*Calothrix confervicola*	C
BG	*Chroococcus submarinus*	C
BG	*Lyngbya confervoides*	C

B = brown algae (Ochrophyta), BG = bluegreen bacteria (Cyanobacteria), G = green algae (Chlorphyta), R = red algae (Rhodophyta), A = Asian, A+ = Asian+, C = Cyptogenic, NP = North Pacific

[1] *Tsunamia transpacifica* is known on debris in the North Pacific, but it has not yet been discovered on either coast.

Note: After this project ended, records of the natural occurrence of *Ptilota serrata* in the Northeast Pacific were found to be incorrect (Guiry and Guiry, 2018), and this cryptogenic species could now be added to this list.

Appendix 9-5. Map of the known JTMD algal species occurring along the outer coast of Washington and Oregon before the tsunami

Source:

Personal and public herbarium databases and state and national checklists accessed July 2014. Base map is from Google Earth.

Site	Pressings	Species	JTMD	% JTMD	Notes
Olympic Nat. Park – Pacific coast	list	200	13	6.5	exposed
Grays Harbor & Jetty	278	106	18	17	oyster
Willapa Bay	589	84	26	31	oyster
Netarts Bay	93	55	9	16	oyster
Boiler Bay	916	232	15	6.5	exposed
Yaquina Bay	401	98	16	16	oyster
Coos Bay	484	102	14	14	logs
Cape Blanco	222	62	2	3.2	exposed

Higher numbers occurred in the sheltered bays.

Some widespread resident JTMD species:
Petalonia fascia, Ectocarpus silulosus var. parvus, Kuckuckia spinosa, Ulva (lactuca, linza, intestinalis), Devaleraea mollis, Scytosiphon lomentaria, Blidingia minima var. minima

JTMD algal species numbers to date (in white)

John Chapman

Chapter 10: Genetics of marine algae arriving on Japanese Tsunami Marine Debris and their invasion threat to the Pacific coast of North America[1]

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[2] Oregon State University, Newport, Oregon, USA

Abstract

Both morphology and genetic markers were used to identify macroalgae on Japanese Tsunami Marine Debris (JTMD) and to compare these species with native populations in Japan and on the Pacific coast of North America. Based on these analyses, gene sequences were obtained and used to identify 50 macroalgal species and to carry out genetic taxonomy on approximately 190 specimens. Our genetic analyses indicated that most JTMD macroalgae had haplotypes that were identical with, or very closely related to, natural populations in the Tohoku region, confirming that they originated from Japan and not from secondary settlement elsewhere. Among the JTMD taxa examined, some species are reported to be distributed on both sides of the Pacific and therefore, their new introduction to the Pacific North American coast may not be regarded as a species-level invasion. However, our genetic comparisons indicated that they are genetically distinct and may cause genetic contamination (e.g., *Blidingia minima, Analipus japonicus, Petalonia fascia* and *Costaria costata*). Some species have already been introduced to the Pacific North American coast by relatively recent anthropogenic introductions (e.g., *Mutimo cylindricus, Undaria pinnatifida* and *Grateloupia turuturu*), but they have not yet spread to the entire Pacific North American coast. These were found to have different haplotypes than those on JTMD. Therefore, the JTMD haplotypes are not only new genetic introductions but they also pose a hybridization risk that would enrich the genetic diversity of the introduced populations.

Introduction

After being carried across the North Pacific on currents from Japan, marine debris from the Great Japan Tsunami of 2011 arrived on the Pacific North American coasts of Alaska, British Columbia, Washington and Oregon and in Hawaii. Many of these items appeared bearing Japanese marine algae. Since the macroalgal species were often healthy and reproductive, there was a possibility that they could establish recruits in North American habitats.

During this project, we identified macroalgal species collected from Japanese Tsunami Marine Debris (JTMD) arriving on Washington and Oregon coasts by both morphological and genetic studies. Marine macroalgae collected from JTMD were preliminarily identified using morphology. However, there were often difficulties due to damage to the specimens during the trans-Pacific trip, the landing and sampling of the debris, and transportation to the laboratory. In addition, definitive species-level identifications were often impossible because of undifferentiated life history stages (juvenile or premature lacking reproductive structures) and poorly-defined morphological boundaries between related species. Our genetic studies provided the opportunity to identify these difficult specimens. Since there was also the possibility that some specimens sampled from the debris originated by settlement of propagules from native North American populations before the debris landed, we also obtained genetic data from the Japanese and North American local (native) populations of the species identified from JTMD. These genetic data were used to distinguish any species newly introduced by JTMD from native or previously introduced species.

Methods

Specimen collection and preservation

Macroalgal specimens obtained from available JTMD items (see Chapter 9) were initially sorted and photographed. The material was then divided into two parts: one part was preserved in 5% formalin in seawater for later morphological study; the second part was preserved in silica gel and mailed to the Kobe laboratory for genetic analysis. Comparative samples of JTMD species were also obtained and preserved from natural habitats in Washington, Oregon and Japan.

Genetic identification of JTMD macroalgae

Genomic DNA was extracted from fresh or silica gel-dried algal tissue of field-collected specimens and of unialgal culture strains housed in the Kobe University Macroalgal Culture Collection (KU-MACC) using a DNeasy Plant Mini Kit (QIAGEN, Hilden, Germany) or QuickExtract Plant DNA Extraction Solution (Epicentre, Madison, Wisconsin, USA) following the manufacturer's instructions. Polymerase chain reaction (PCR) amplifications of the chloroplast *psb*C, *rbc*L, *atp*H-*atp*I region, mitochondrial *cox*1, *cox*3, *cob*-*cox*3 region, and nuclear 18S rDNA and its internal transcribed

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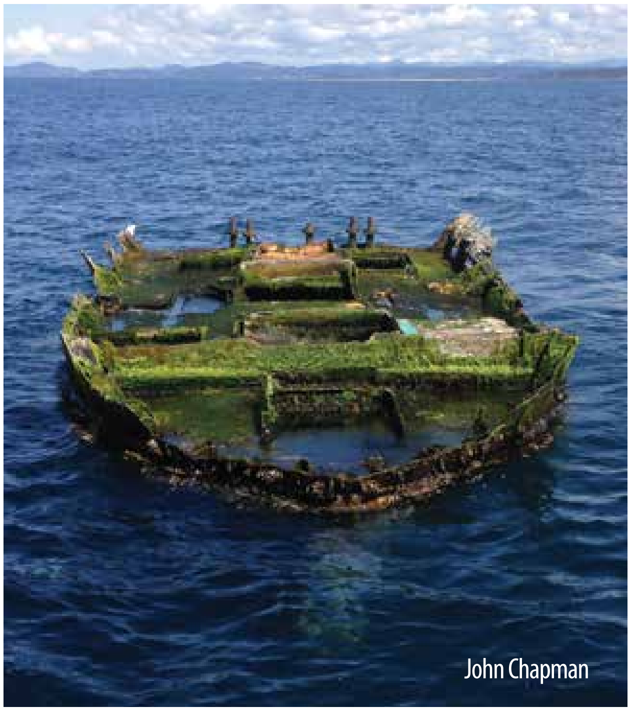
[1] A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 74-81.


John Chapman

Gayle Hansen

sequence (ITS) region and 28S rDNA were carried out using the KOD FX (ToYoBo, Osaka, Japan) PCR enzyme and the TaKaRa PCR Thermal Cycler Dice (Takara Bio, Kusatsu, Japan). After polyethylene glycol (PEG) purification (Lis, 1980), PCR products were sequenced using the CE DTCS Quick Start Kit (Beckman Coulter, Fullerton, California, USA) and the CEQ8000 DNA analysis system (Beckman Coulter) according to the manufacturer's instructions, or were sequenced by a DNA sequencing service (FASMAC, Atsugi, Japan).

The molecular phylogenetic analyses used published and newly determined sequence data. Alignments were prepared using the program MAFFT v.6 (Katoh and Toh, 2008) and then manually adjusted prior to phylogenetic analyses. For maximum likelihood (ML) analysis, we used RAxML GUI v.1.31 (Silvestro and Michalak, 2012), conducting 10,000 Rapid Bootstrap searches followed by a ML search, with the GTR + G model for each codon position of each organelle gene or for each position of each nuclear region. To examine genetic relationships among the haplotypes or genotypes, statistical parsimony networks were created using TCS v.1.21 (Clement et al., 2000) based on the DNA sequences of chloroplast or mitochondrial haplotypes, or nuclear genotypes.

Results

Molecular phylogeny and biogeographical analyses of representative taxa

We obtained DNA sequence data from 190 specimens collected and sent to Kobe University. The list of specimens examined for genetic analyses is presented in Appendix 10-1. Below are representative taxa that were identified.

Ulva species

Molecular phylogenetic analyses of *Ulva* species of JTMD specimens based on nuclear ITS1-5.8S-ITS2 rDNA sequences revealed that at least 7 species (A to G) were included: *U. compressa, U. flexuosa*?, *U. lactuca, U. linza, U. pertusa/ australis, U. prolifera* and *U. simplex* (Figure 10-1). Among them, *U. simplex* has not been reported earlier from the Pacific coast of North America.

Ulva lactuca (green algae, Ulvales)

Ulva lactuca is distributed both in Japan and Pacific North America, but the JTMD specimens were genetically distinct from those in Hokkaido, British Columbia, Washington, and Oregon (Figure 10-2).

Ulva pertusa/australis (green algae, Ulvales)

Ulva pertusa, a common intertidal and subtidal species in Japan, was collected from several JTMD items. The species has been introduced world-wide, and has already been recorded from Washington and Oregon (Figure 10-3). Therefore, our study of the species was mainly focused on the large JTMD items whose geographic origin was unclear, such as a derelict (unidentified) boat, described below. We examined the *atp*I-H and *cob-cox*3 DNA sequences of *Ulva pertusa/U. australis* specimens collected from the derelict boat from off-shore at Seal Rock, Oregon on April 9, 2015 (see image above), and compared them to those specimens from northern Japan based on Hanyuda et al. (2016) and newly collected specimens from Tohoku. The haplotype of the Seal Rock boat specimens agreed with a haplotype found in Ainohama, Iwate, although this haplotype has not been found in other areas including central/southern Honshu (Hanyuda et al., 2018). Therefore, it is strongly suggested that the unidentified boat originated from Tohoku as JTMD.

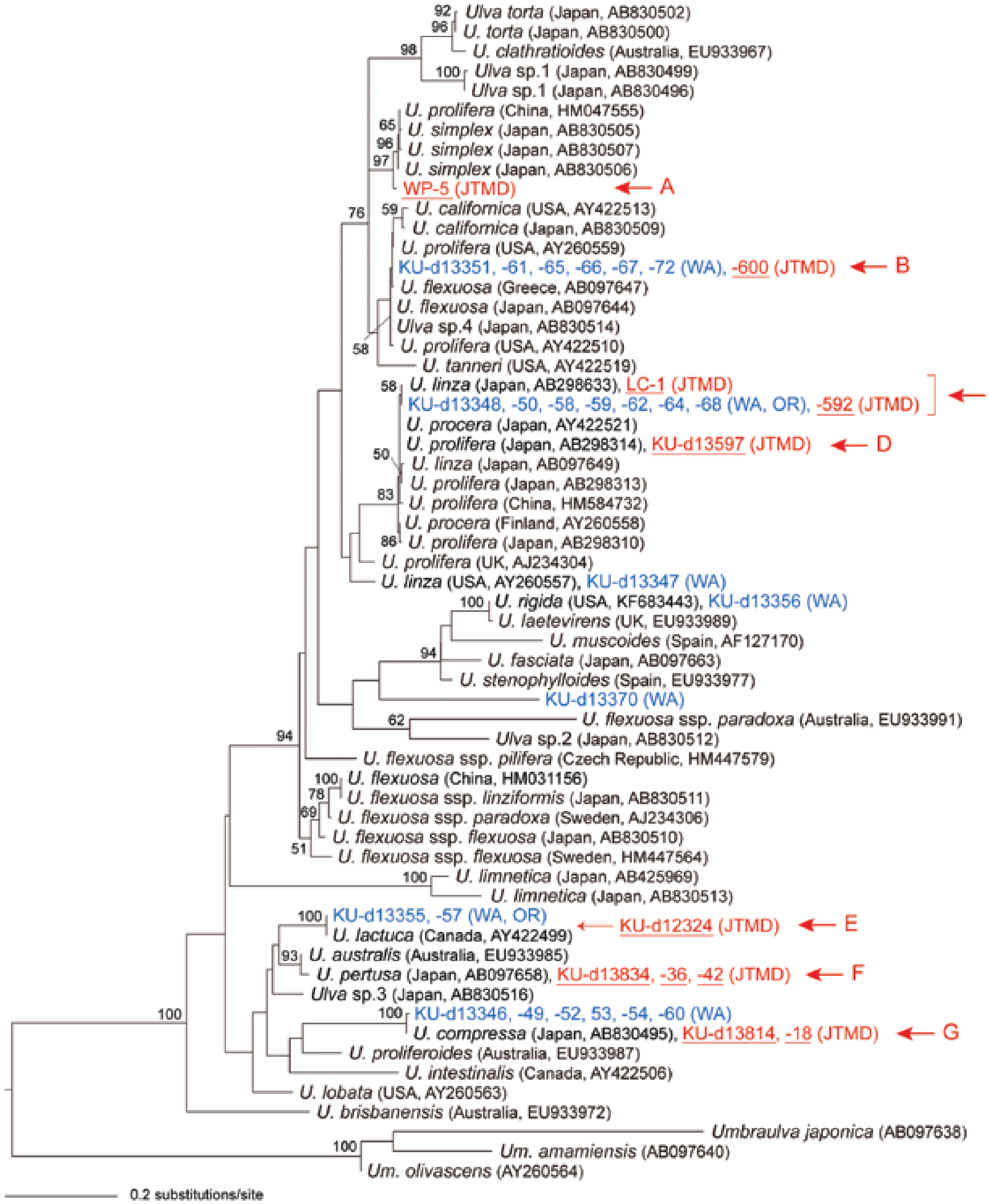


Figure 10-1. Molecular phylogeny of *Ulva* species. Maximum likelihood tree based on DNA sequences of nuclear rDNA, ITS1, 5.8S and ITS2. JTMD specimens which are 7 species (A to G) are shown in red letters, and field-collected North American specimens are shown in blue letters.

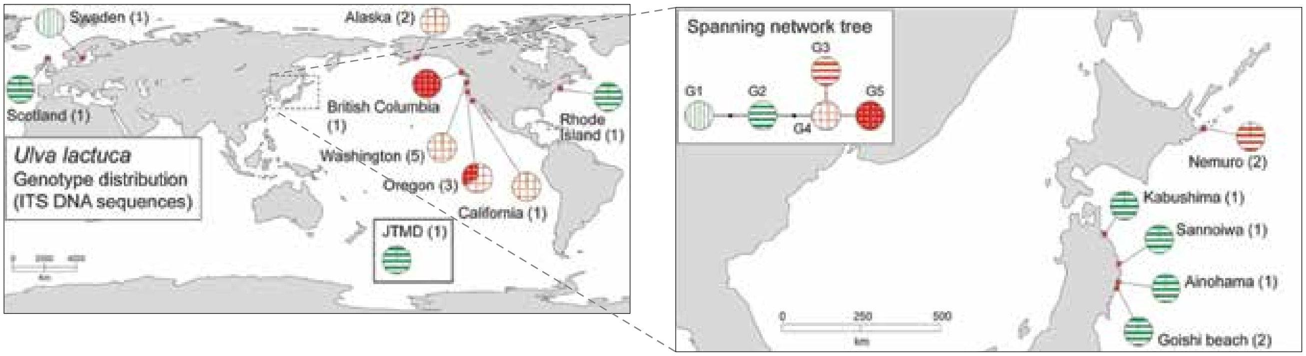


Figure 10-2. Geographical distributions of genetic types based on the internal transcribed sequence (ITS) region sequence data of *Ulva lactuca*, and the locality of *U. lactuca* samples and the distribution of ITS genotypes. Haplotypes G1 and G2 are shown green colour, and remaining three haplotypes (G3 to G5) are shown red colour.

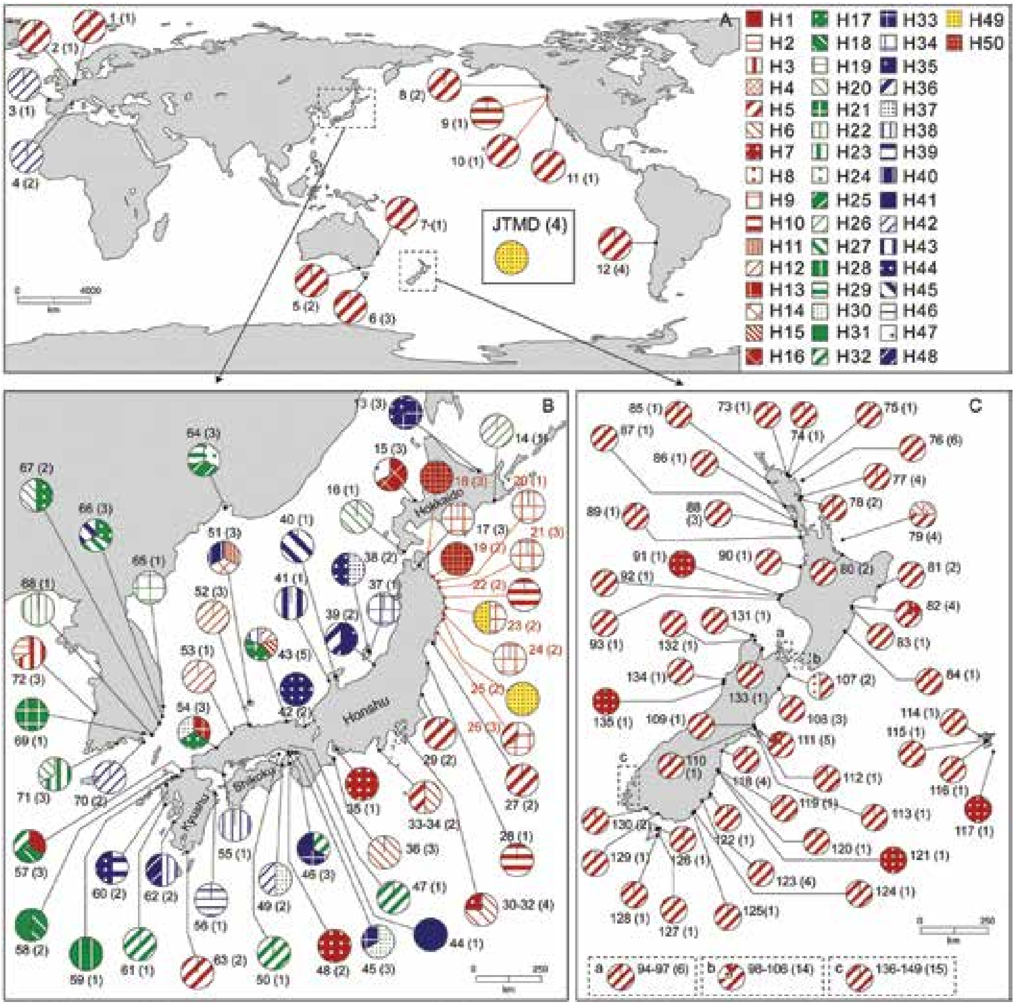


Figure 10-3. Geographical distributions of genetic types revealed from *atp*I-H and *cob-cox*3 DNA sequences of *Ulva pertusa/australis,* and the locality of *U. pertusa/australis* samples and the distribution of *atp*I-H and *cob-cox*3 haplotypes. S1–S145 indicate the collection sites. Numbers in parentheses show examind specimens. Haplotypes H1–H48 (H1–H16: red, H17–H32: green, H33–H48: blue) were recognized in Hanyuda et al. (2016), and H49–H51 were recognized in Hanyuda et al. (2018).

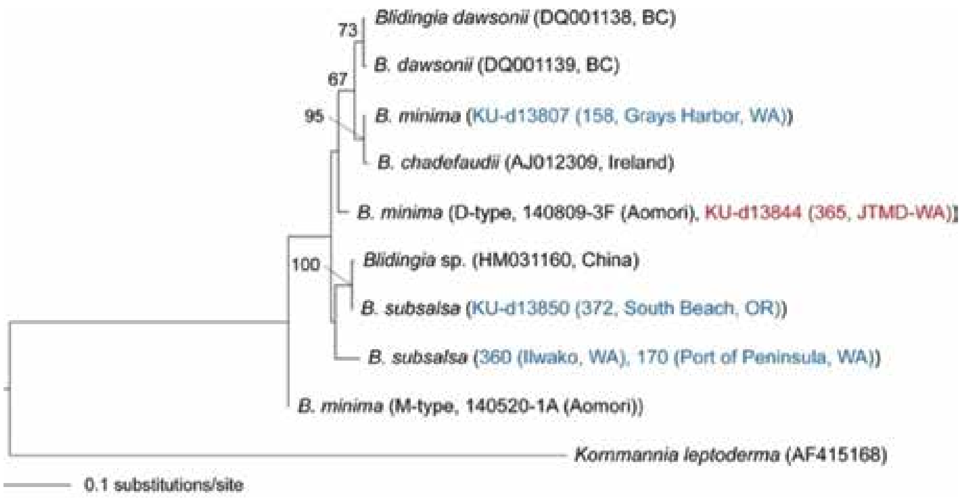


Figure 10-4. Maximum likelihood (ML) tree of *Blidingia minima* based on the nuclear rDNA ITS region sequences (571 bp). Numbers at nodes indicate bootstrap values in ML analysis. Only bootstrap values >50% are shown. JTMD specimens are shown in red letters, and field-collected Pacific North American specimens are shown in blue letters.

Blidingia minima (green algae, Ulvales)

Blidingia species are upper intertidal green algae, which are often difficult to identify at the species level solely based on morphology. We examined *Blidingia* specimens collected on debris in Washington (KU-d13844), confirmed that they had a sequence identical to *B. minima* collected at Aomori, Tohoku, and identified them as *B. minima* (Figure 10-4). Native North American *Blidingia* specimens (Oregon, Washington, and British Columbia) were genetically distinct from JTMD and Japanese specimens.

Petalonia fascia (brown alga, Ectocarpales *s.l.*)

Petalonia fascia is a common annual to ephemeral brown alga growing on diverse substrates including artificial structures in the intertidal zone and was frequently found on JTMD. This species has broad distributional ranges in temperate and coldwater seas. Since the gametophytes (erect thalli) grow rather rapidly, it is difficult to determine the origin of the individuals on JTMD. If the JTMD becomes cast ashore or stays near the shore for some days, zoids (zoospores) from mature crustose sporophytes of the natural population may also attach on JTMD and become emergent within a couple of weeks. Therefore, in order to clarify the origin of the *P. fascia* individuals collected from JTMD, we compared the *cox*3 gene sequences of the specimens from JTMD and from the field in Japan and North American coasts. We also added some specimens collected worldwide for comparisons in order to clarify the global biogeography of the species.

In the spanning network analyses, the haplotypes based on the mitochondrial *cox*3 gene suggested the occurrence of two genetic groups: group-a comprised of populations in Honshu, the Southern Hemisphere, and a part of Europe; and group-b comprised of populations in Hokkaido, Pacific and Atlantic America, and Europe (Figure 10-5). The haplotypes H1, H2, and H3 were somewhat distant from H4-H8, but sometimes found mixed in Honshu, Japan (i.e., Tatehanazaki and Oiso). In contrast, the haplotypes H9–H15 were rather close. The haplotypes of the specimens on JTMD were all of group-a (haplotypes with blue and green colours), whereas field-collected specimens from Washington, Oregon and California were all of group-b (haplotypes with red colour). Therefore, the *P. fascia* specimens were considered to have originated from Japan. Although H2 was dominant in Aomori and Iwate populations of the Tohoku region, JTMD specimens showed rather high genetic divergence (four haplotypes: H2, H4, H6 and H8). This may be explained by the lack of specimens from the southern Tohoku area.

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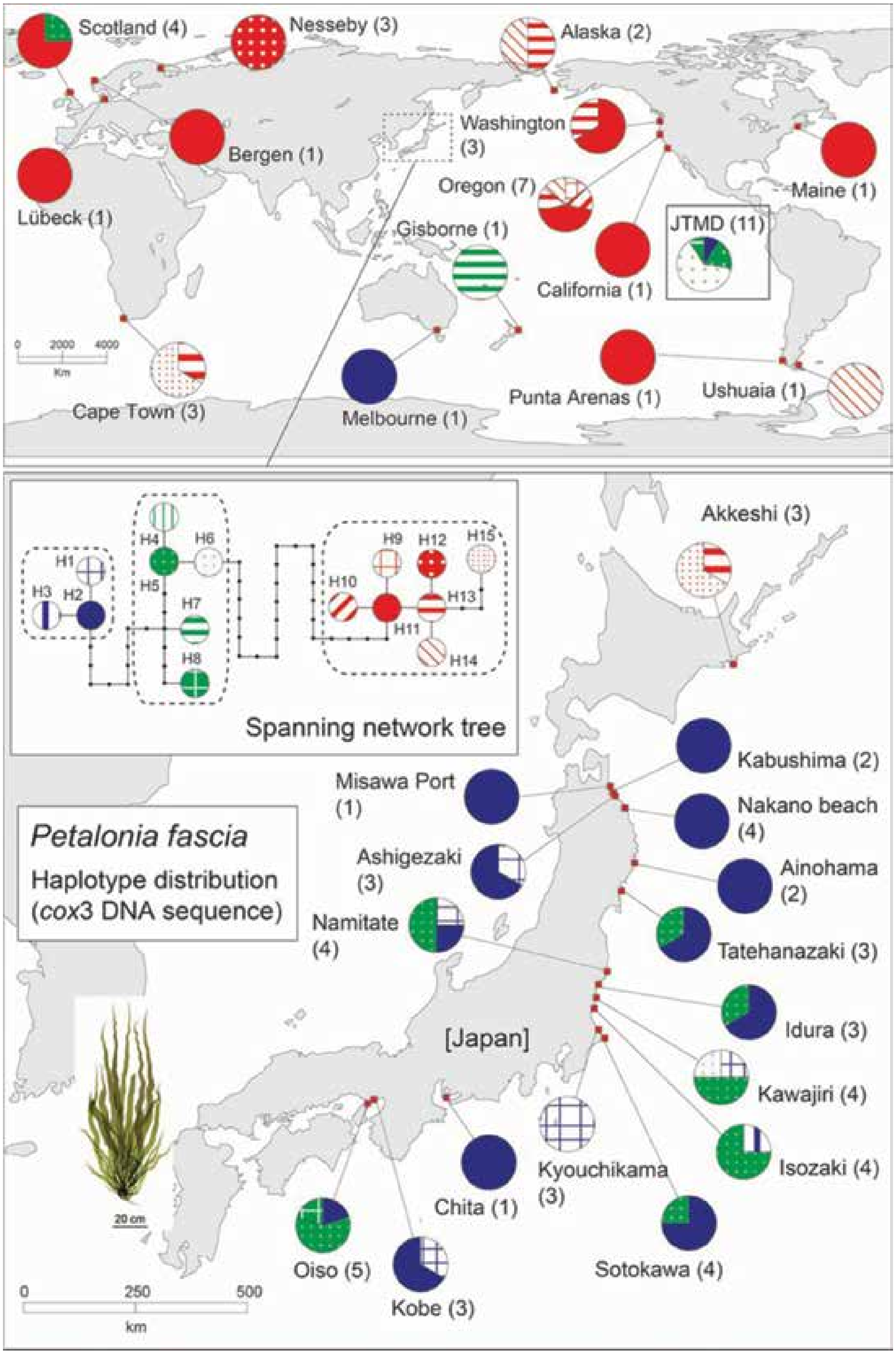


Figure 10-5. Spanning network tree based on the *cox*3 sequence data of *Petalonia fascia*, and the locality of *P. fascia* samples and the distribution of *cox*3 haplotypes.

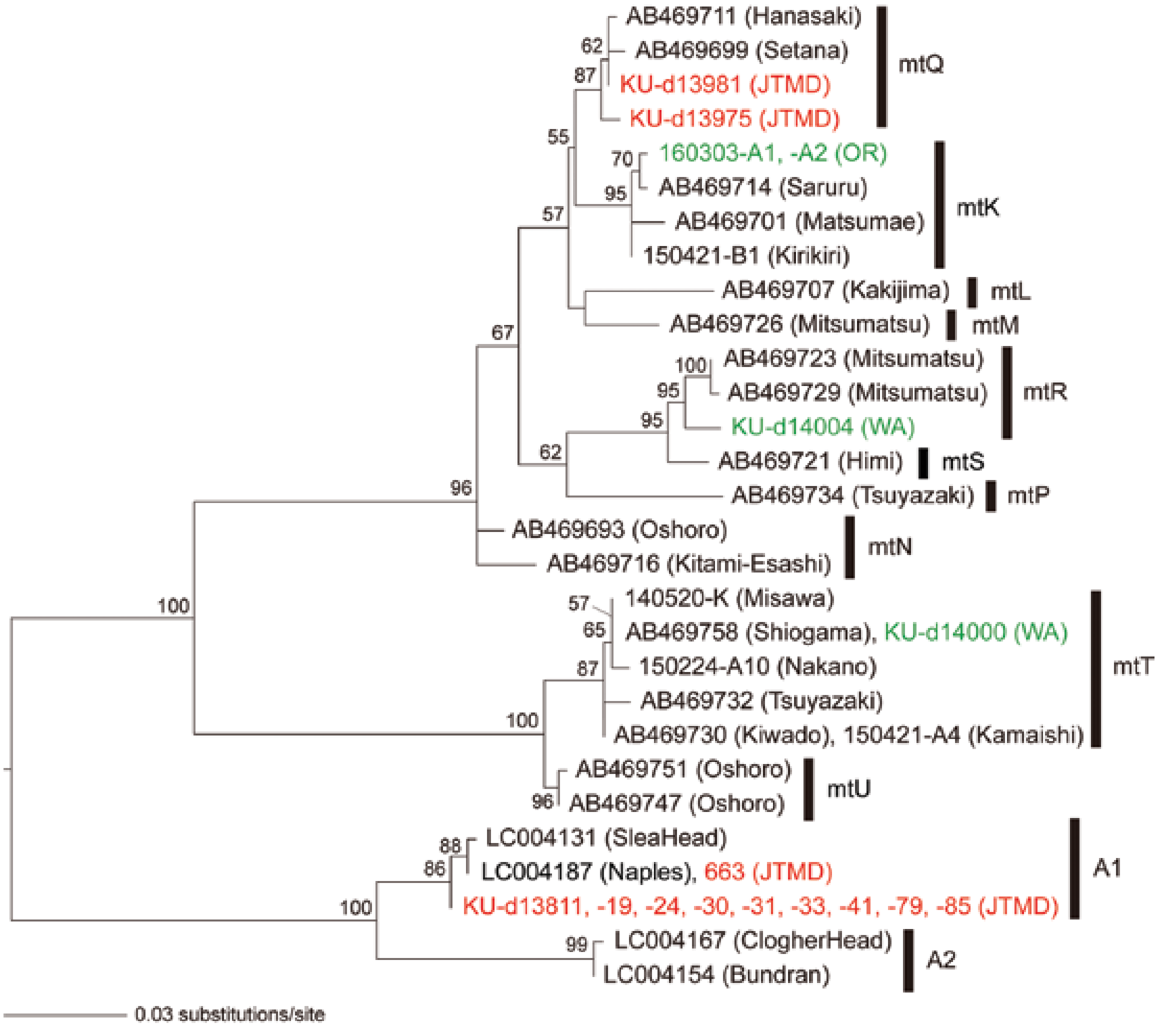
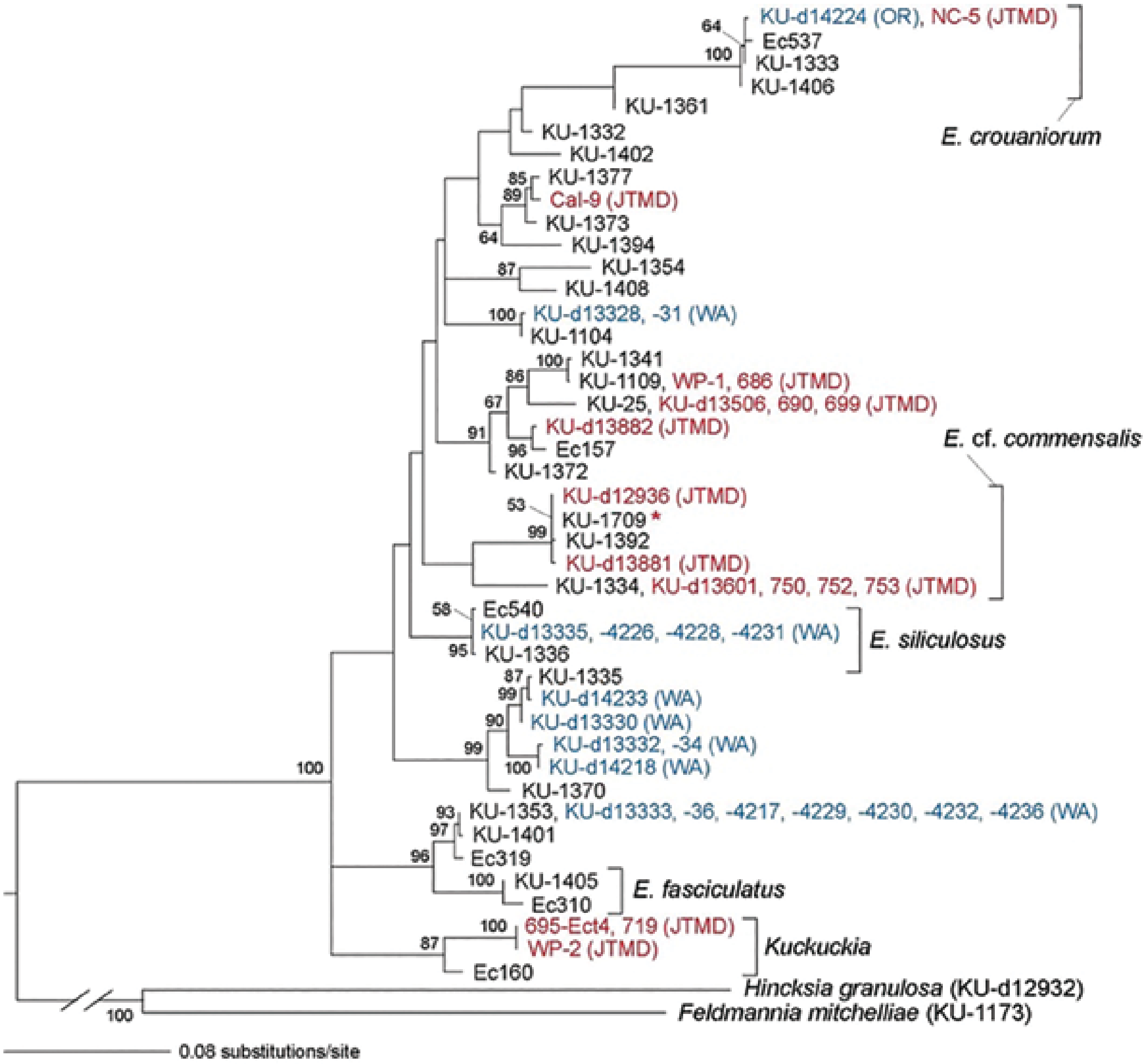


Figure 10-6. Maximum likelihood (ML) tree for *Scytosiphon lomentaria* based on the mitochondrial *cox*3 gene sequences (500 bp). Numbers at nodes indicate bootstrap values in ML analysis. Only bootstrap values >50% are shown. JTMD specimens are shown in red letters, and field-collected Pacific North American specimens are shown in green letters.

Scytosiphon lomentaria (brown alga, Ectocarpales *s.l.*)

Scytosiphon lomentaria is a common annual to ephemeral brown alga growing on diverse substrates including artificial structures in the intertidal zone and has been frequently found on JTMD. *S. lomentaria* is taxonomically very close to *Petalonia fascia* and has similar life history and ecological characters. The species also has broad distributional ranges in temperate and coldwater seas. Therefore, in order to clarify the origin of the *S. lomentaria* individuals collected from JTMD, we compared the *cox*3 gene sequences of the specimens from JTMD and from the field in Japan and North American coasts. We also added some specimens collected worldwide for comparisons in order to clarify the global biogeography of the species.

Our results show that JTMD *Scytosiphon* included two independent lineages, one genetically close to those from Hokkaido (mtQ) and the other genetically close to those from Europe (A1). Field-collected specimens from Oregon and Washington belonged to three independent lineages (mtK, mtR, mtT) which were genetically close to various localities in Japan (Figure 10-6). This suggests that the intercontinental introductions of this species may have frequently occurred and the original distributional pattern has been disturbed. Species level taxonomy of *S. lomentaria* needs further examination, so it is possible that these lineages correspond to independent species, or some intra-species level taxa such as subspecies or variety.



*KU-d12934 (CB-4, JTMD), -d12936 (CB-5, JTMD), -d13501 (108, JTMD), -d13575 (116, WA), -d13576 (117, WA), -d13829 (223, JTMD), -d13837 (234, JTMD), 695-Ect3 (JTMD), 698 (JTMD), and 707 (JTMD) had the identical sequence with KU-1709.

Figure 10-7. Maximum likelihood (ML) tree of *Ectocarpus* species based on the mitochondrial *cox*3 gene sequences (665 bp). Numbers at nodes indicate bootstrap values in ML analysis. Only bootstrap values >50% are shown. JTMD specimens are shown in red letters, and field-collected Pacific North American specimens are shown in blue letters.

Ectocarpus spp. (brown algae, Ectocarpales *s.l.*)

Filamentous brown algae were frequently encountered on JTMD, but they are generally difficult to identify solely based on morphology. In addition, the species-level taxonomy of *Ectocarpus* and related taxa is rather confused because although there have been around ten phylogenetic entities identified worldwide, perhaps corresponding to species, many of them do not have formally described names at present. In the current study, we examined their *cox*3 gene sequences and found that they belong to 8 to 9 *Ectocarpus* species and one *Kuckuckia* species (Figure 10-7). Two of the *Ectocarpus* taxa had sequences identical or very close to *E. croaniorum* and *E. siliculosus*, and were identifiable to these taxa, but it was difficult identify all of them to the species level by genetic study because taxonomic revision of the genus *Ectocarpus* has not been completed and species names are not assigned to some clades. However, it is noteworthy that some of the clades (plausible species) of JTMD specimens have not been recorded from Pacific North American coasts.

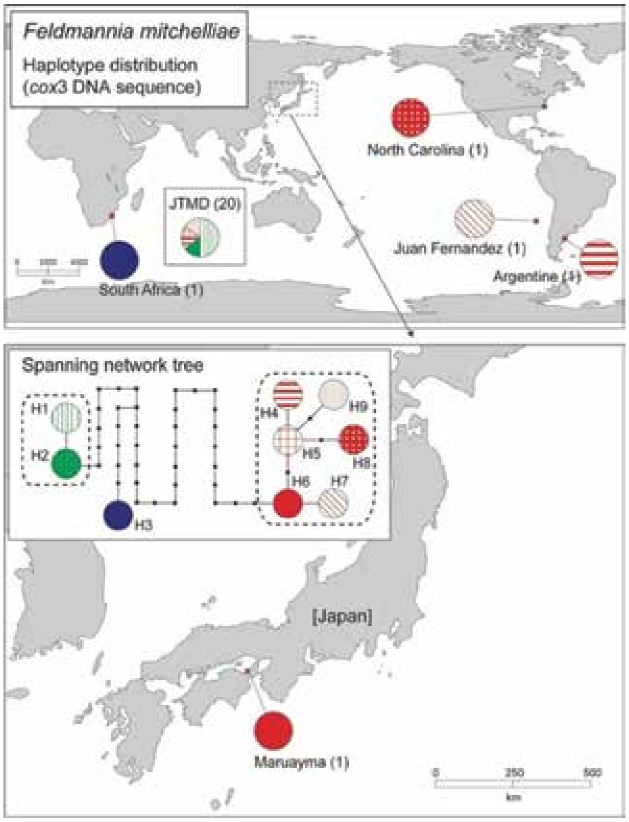


Figure 10-8. Spanning network tree based on the *cox*3 sequence data of *Feldmannia mitchelliae*, and the locality of *F. mitchelliae* samples and the distribution of *cox*3 haplotypes.

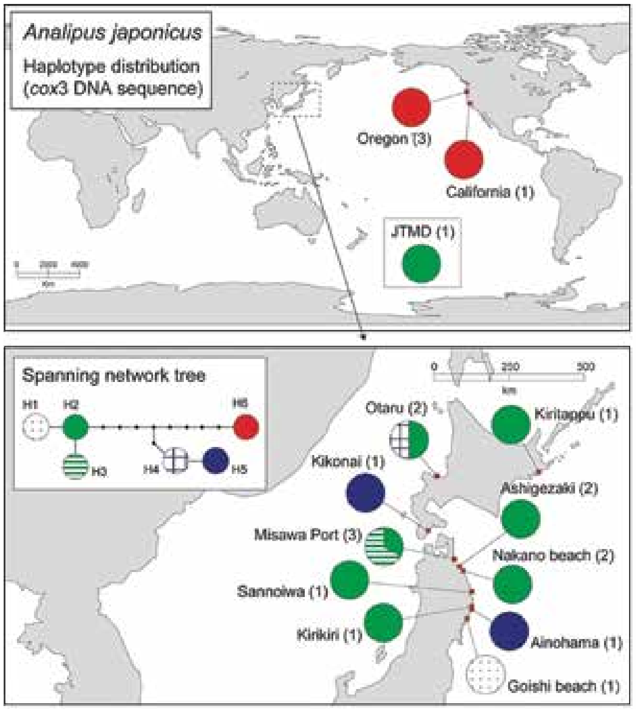


Figure 10-9. Spanning network tree based on the *cox*3 sequence data of *Analipus japonicus*, and the locality of *A. japonicus* samples and the distribution of *cox*3 haplotypes.

Feldmannia mitchelliae (brown algae, Ectocarpales *s.l.*)

Feldmannia species are filamentous brown algae resembling *Ectocarpus*, but primarily distinguished from *Ectocarpus* in the chloroplast morphology (discoid vs. ribbon-shaped). However, the vegetative morphology is rather plastic and species level taxonomy is often difficult. In this study, we identified the JTMD specimens as *F. mitchelliae* by *cox*3 gene sequences (Figure 10-8). JTMD *F. mitchelliae* included several haplotypes of *cox*3, but unfortunately data of the genetic types of local populations on Pacific North American coasts were not available at time of publication.

Analipus japonicus (brown algae, Ralfsiales)

Analipus japonicus is a common brown alga that grows on intertidal rocks or on mussels in cold temperate and colder seas. This species was found on the Misawa floating dock landing in Oregon as JTMD. Upright thalli are annual but the basal part of the thallus is perennial. The species is distributed on both sides of the North Pacific, from Tohoku region to Hokkaido in Japan and from Alaska to California on Pacific North American coasts. Genetic comparison using *cox*3 DNA sequences revealed that North American and Japanese populations are genetically distinct, although they are relatively closely related and Japanese populations show high genetic divergence (Figure 10-9).

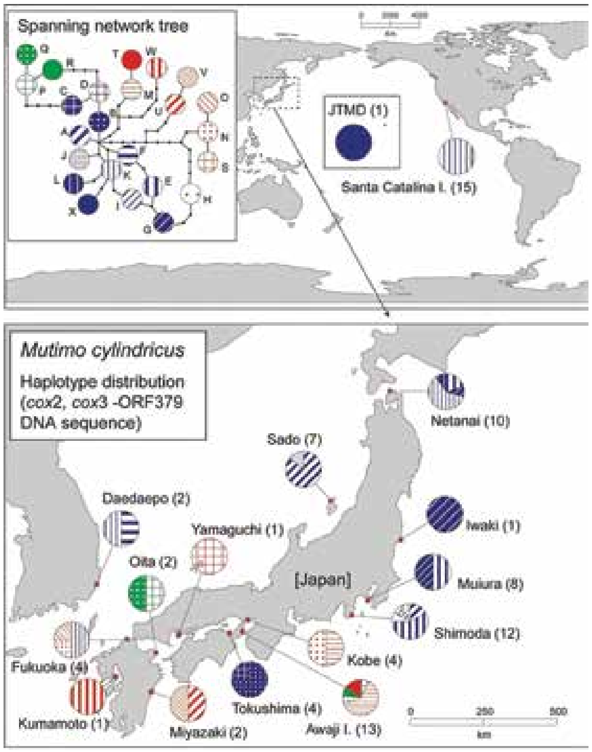


Figure 10-10. Spanning network tree based on the *cox*2 and *cox*3-ORF379 sequence data of *Mutimo cylindricus*, and the locality of *M. cylindricus* samples and the distribution of haplotypes.

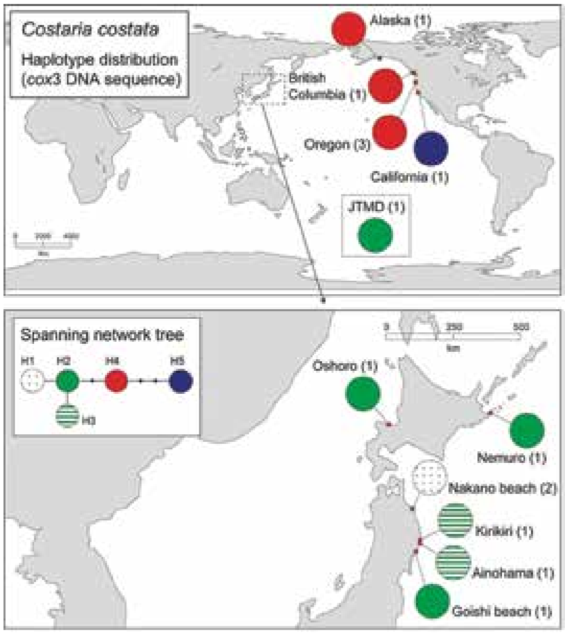


Figure 10-11. Spanning network tree based on the *cox*3 sequence data of *Costaria costata*, and the locality of *C. costata* samples and the distribution of *cox*3 haplotypes.

Mutimo cylindricus (brown algae, Tilopteridales)

Mutimo cylindricus is an annual brown alga originally distributed in northeastern Asia. It was shown to be introduced to Santa Catalina Island, California (Kogishi et al., 2010 as *Cutleria cylindrica* later transferred to genus *Mutimo* in Kawai et al., 2012), perhaps from Tohoku, Japan (Figure 10-10). The California population was dominated by female, asexual gametophytes reproducing by parthenogenesis. *Mutimo cylindricus* found on JTMD was shown to have a distinct genetic type, and is likely a sexual strain. Therefore, new introductions may show different propagation patterns from the California population.

Costaria costata (brown algae, Laminariales)

Costaria costata, an annual kelp species, was found on the Misawa floating dock landing in Oregon. The species is distributed on both sides of the North Pacific, from the Tohoku region to Hokkaido in Japan and from Alaska to California on Pacific North American coasts. Genetic comparison using *cox*3 DNA sequences revealed that North American and Japanese populations are genetically distinct, although they are relatively closely related (Figure 10-11).

Saccharina japonica (brown algae, Laminariales)

Saccharina japonica is a biennial kelp species exceeding several meters in length, and constitutes one of the most important ecological elements in colder seas in Japan. It was found on the Misawa floating dock landing in Oregon. The species is distributed in cold water regions of Tohoku and Hokkaido, Japan (Figure 10-12). The species does not occur in Pacific North America, and therefore there is concern about the possibility of an introduction of this species. In addition, *Saccharina* species are genetically very closely related and the occurrence of interspecies hybrids (and sometimes even hybrids between genera) is known. Therefore, there is concern about genetic contamination of native populations that could cause strong disruptions to local ecosystems.

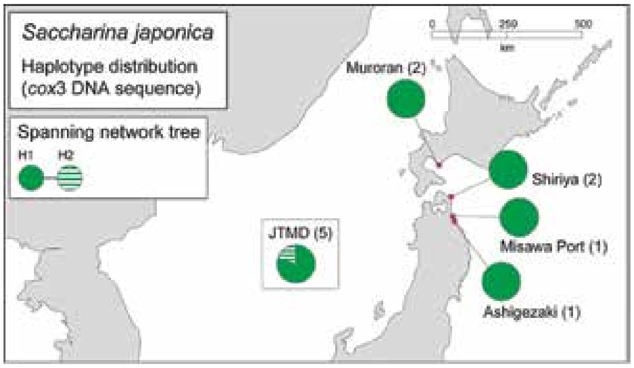


Figure 10-12. Spanning network tree based on the *cox*3 sequence data of *Saccharina japonica*, and the locality of *S. japonica* samples and the distribution of *cox*3 haplotypes.

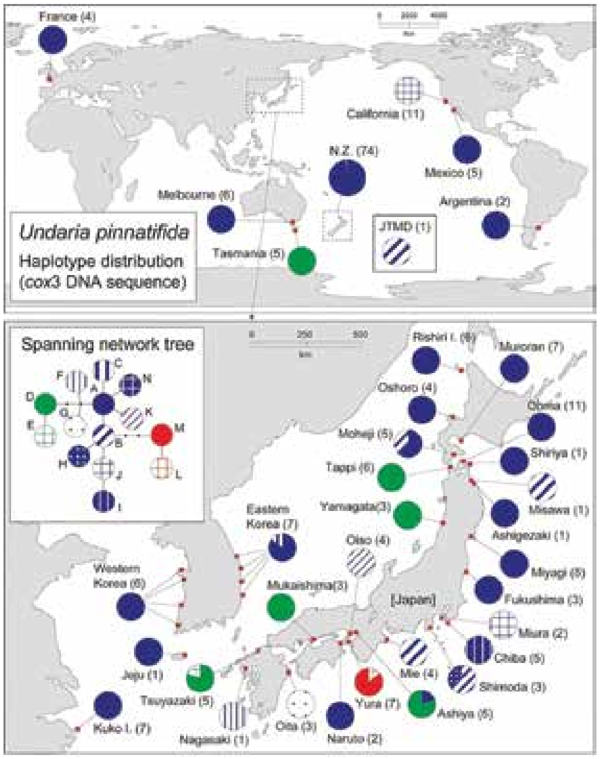


Figure 10-13. Spanning network tree based on the *cox*3 sequence data of *Undaria pinnatifida*, and the locality of *U. pinnatifida* samples and the distribution of *cox*3 haplotypes.

Undaria pinnatifida (brown algae, Laminariales)

Undaria pinnatifida was found on the Misawa floating dock landing in Oregon. The species is an annual kelp constituting an important ecological element of temperate seas. The original distributional range of the species is northeastern Asia, but it has been introduced and has been established widely both in the Northern and Southern Hemispheres (Figure 10-13). On the Pacific coast of North America, the species has been introduced to California and Mexico, but it has not spread north to Oregon. Therefore, there is concern about a new introduction of this species because it could cause considerable disturbance to the local ecosystems, as well as to fisheries.

Grateloupia turuturu (red algae, Halymeniales)

Grateloupia turuturu is an annual red alga with branched membranous thalli. The original distributional range of this species is northeastern Asia, but it has been introduced to various areas in Europe, and to the Pacific and Atlantic coasts of North America. On the Pacific coast of North America it has been reported from California and Mexico, but it has not been reported from Oregon. Based on the *rbc*L DNA sequence, the specimen collected from JTMD had the same haplotype as that reported from Mexico (Figure 10-14). However, resolution of this gene region is considered to be rather low, because it is a conserved region. Therefore, it is necessary to use a gene region with a faster mutation rate in order to distinguish the JTMD specimen from existing California and Mexico populations.


Gayle Hansen

Dr. Takeaki Hanyuda holding *Undaria pinnatifida* found on the docks in Misawa, Japan, for comparison with JTMD material.

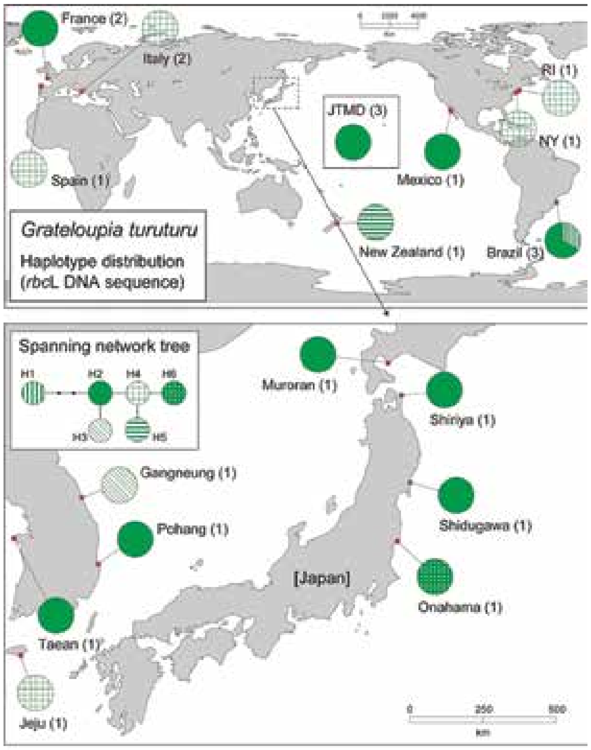


Figure 10-14. Spanning network tree based on the *rbc*L sequence data of *Grateloupia turuturu*, and the locality of *G. turuturu* samples and the distribution of *rbc*L haplotypes.


Hideaki Maki

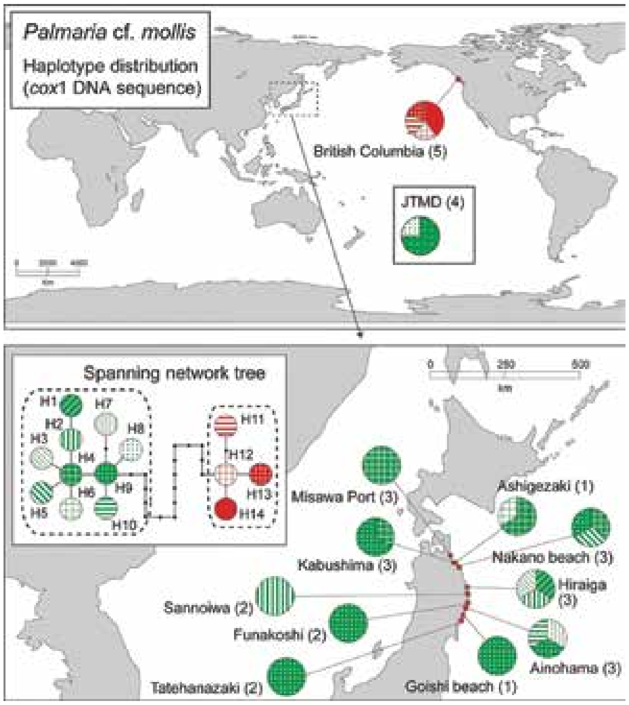


Figure 10-15. Spanning network tree based on the cox1 sequence data of *Palmaria palmata/ P. mollis*, and the locality of *Palmaria palmata/P. mollis* samples and the distribution of *cox*3 haplotypes.

Palmaria palmata/mollis **(red algae, Palmariales)**[2]

Palmaria palmata (auct. japon.) was collected from the Misawa floating dock landing in Oregon. *Palmaria palmata* is an annual foliose red alga distributed in wide ranges of colder seas, however, there have been taxonomic problems in the genus and species-level taxonomy. *Palmaria palmata* (auct. japon.) was considered conspecific to *Palmaria mollis* distributed on the coasts of Pacific North America, an important ecological element due to its relatively large size and abundance. In our study, the comparisons of *cox*1 gene haplotypes of Japanese and JTMD-derived specimens suggested that Japanese *Palmaria palmata* collected on JTMD agreed with the field-collected specimens from northern Tohoku, but they also suggested that they were genetically distant by about 20 bp in *cox*1 sequences from native (local) populations of *P. mollis* in British Columbia (Figure 10-15). If the taxa (Japanese *P. palmaria* and *P. mollis*) are independent species, there is concern about a new introduction of a non-indigenous species, and if they are conspecific, there is concern about genetic contamination of native populations. Even if they are taxonomically concluded to be independent species, considering their close genetic relationship, there is still a possibility that they could cross to form hybrids and cause genetic contamination by introgression. *Palmaria palmata* is widely used as a food (and is sold commercially as 'dulse') in northern Europe and eastern North America. *P. mollis* is less frequently used as a food source, but its introduction could still cause economic damage in addition to the risks of disturbance to the local ecosystems.

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[2] Shortly after our study completed in 2017, *Palmaria mollis* from the northeastern Pacific was renamed *Devaleraea mollis* (Setchell and Gardner) Saunders, Jackson and Salomaki, but no decision on the identity of *Palmaria palmata* (auct. japon.) has been made.

Lynn Ketchum

Discussion

Since the 1990s, genetic sequencing has been used increasingly to identify marine algae and to map their distributions. Sequences are particularly important to use in some species due to their complex life histories, limited taxonomic features and morphological plasticity. These complications arose with JTMD algae. After the long trip over, the size and form of the species often varied from the literature descriptions. Reproductive structures essential for identification were not present in all of the samples. Besides, more often than not, the material would arrive dried out, heavily epiphytized or disintegrating, making it impossible to observe basic features like chloroplast morphology. Although attempts were made to obtain complete and properly preserved collections, this was difficult to achieve because sampling often had to be carried out by non-specialists, and errors could easily occur. In order to improve the accuracy of identification and compensate for these problems, we applied genetic analyses using selected genetic markers. Based on these analyses, we obtained and used gene sequences for the taxonomic assessment of approximately 190 specimens and genetically identified 50 species from JTMD macroalgae.

Genetic data were also used to confirm that macroalgal species sampled from JTMD originated from Japan, and not from the Pacific coast of North America by the secondary attachment of local macroalgae after debris arrival on the coast. Some ephemeral taxa such as filamentous brown algae (e.g., ecotocarpoids) and green algae (ulvoids) may be able to settle on JTMD and grow on them rather rapidly, so this examination was particularly important. In addition, some JTMD species were known to occur on both sides of the Pacific by natural distribution or by anthropogenic introductions before the Great Japan Tsunami of 2011. Therefore, it was necessary to compare the three entities (i.e., Japanese natural population, JTMD macroalgae and North American natural population) by appropriate genetic markers.

Our genetic analyses demonstrated that most JTMD macroalgae had haplotypes that were identical with, or very close to, natural populations in the Tohoku region, confirming that they originated in Japan and not from secondary settlement in North America. Among the JTMD taxa examined, some species are reported to occur on both sides of the North Pacific and therefore, their new introduction to the Pacific coasts of North America may not be regarded as a species-level invasion. However, our genetic comparisons have indicated that they are genetically distinct and may cause genetic contamination (e.g., *Blidingia minima, Analipus japonicus, Petalonia fascia* and *Costaria costata*). Some species were found to already occur on the Pacific coast of North America due to relatively recent anthropogenic introductions (e.g., *Mutimo cylindricus*, *Undaria pinnatifida* and *Grateloupia turuturu*), but they have not yet spread to Oregon, and were found to have different haplotypes than those on debris. Therefore, these new introductions will still pose the risk of accelerating the dispersal of these non-indigenous species by enriching the genetic diversity of the introduced populations.

Genetic analyses have revealed the species diversity of the JTMD macroalgae in taxonomically difficult taxa such as *Ulva* spp. and *Ectocarpus* spp. Although the species level taxonomy of *Ectocarpus* is still not fully resolved based on existing genetic data, we consider that there are about a dozen species in the genus. The fact that at least 7 taxa (corresponding to more than half of all taxa worldwide) have been found on JTMD suggests that their natural distributions may be considerably influenced by the patterns of debris dispersal.

Acknowledgements

We are grateful to Dr. Eric Henry for his valuable comments. This work was supported by the Japanese Ministry of the Environment through the North Pacific Marine Science Organization (PICES) and the JSPS Grants-in-Aid for Scientific Research (No. 26440217) to T.H. The U.S. Environmental Protection Agency provided laboratory space for the Oregon part of this study.

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Allan Pleus

Lynn Ketchum

Chapter 10 Appendix

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
6-Jun-12	Oregon floating dock	JTMD	#3	KU-d12315	*Neodilsea yendoana*
6-Jun-12	Oregon floating dock	JTMD	#4	KU-d12316	*Pyropia yezoensis*
6-Jun-12	Oregon floating dock	JTMD	#5A	KU-d12317	*Desmarestia japonica*
6-Jun-12	Oregon floating dock	JTMD	#6a	KU-d12319	*Saccharina japonica*
6-Jun-12	Oregon floating dock	JTMD	#6b	KU-d12320	*Saccharina japonica*
6-Jun-12	Oregon floating dock	JTMD	#7	KU-d12321	*Saccharina japonica*
6-Jun-12	Oregon floating dock	JTMD	#8	KU-d12322	*Saccharina japonica*
6-Jun-12	Oregon floating dock	JTMD	#9	KU-d12323	*Saccharina japonica*
6-Jun-12	Oregon floating dock	JTMD	#10	KU-d12324	*Ulva lactuca*
15-Jun-12	Washington State debris boat	JTMD	WA #1	KU-d12356	*Saccharina japonica*
15-Jun-12	Washington State debris boat	JTMD	WA #2	KU-d12357	*Ulva pertusa/australis*
15-Jun-12	Washington State debris boat	JTMD	WA #3a	KU-d12358	*Chondrus giganteus*
15-Jun-12	Washington State debris boat	JTMD	WA #3b	KU-d12359	*Grateloupia turuturu*
15-Jun-12	Washington State debris boat	JTMD	WA #4	KU-d12360	*Cladophora albida*
15-Jun-12	Washington State debris boat	JTMD	WA #5	KU-d12361	*Grateloupia livida*
28-Jan-13	Seaview rusty pipe	JTMD	2	KU-d12822	*Palmaria* cf. *mollis*
14-Mar-13	Ponsler Boat	JTMD	3	KU-d12823	*Punctaria latifolia*
22-Mar-13	Jockey Cap boat	JTMD	4	KU-d12824	*Petalonia fascia*
21-Feb-13	Horsefall Beach boat	JTMD	5	KU-d12825	*Feldmannia mitchelliae*
22-Mar-13	Jockey Cap boat	JTMD	6	KU-d12826	*Feldmannia mitchelliae*
5-Jan-13	Mosquito Creek dock	JTMD	8	KU-d12828	*Feldmannia mitchelliae*
28-Jan-13	Seaview rusty pipe	JTMD	10	KU-d12830	*Petalonia fascia*
6-Feb-13	Glenden Beach boat	JTMD	11	KU-d12831	*Petalonia fascia*
14-Mar-13	Ponsler Boat	JTMD	12	KU-d12832	*Petalonia fascia*
21-Feb-13	Horsefall Beach boat	JTMD	15	KU-d12835	*Petalonia zosterifolia*
5-Jan-13	Mosquito Creek dock	JTMD	17	KU-d12837	*Ceramium cimbricum*
2-Jan-13	HMSC outfall	JTMD?	21	KU-d12841	*Chaetomorpha linum*
28-Jan-13	Seaview rusty pipe	JTMD	SV-15-4	KU-d12924	*Palmaria* cf. *mollis*
5-Jan-13	Mosquito Creek dock	JTMD	M-17	KU-d12920	*Codium fragile*
21-Feb-13	Horsefall Beach boat	JTMD	HF-4	KU-d12928	*Polysiphonia morrowii*
21-Feb-13	Horsefall Beach boat	JTMD	HF-48	KU-d12927	*Petalonia zosterifolia*
28-Jan-13	Seaview rusty pipe	JTMD	SV-55	KU-d12915	*Alaria crassifolia*
28-Jan-13	Seaview rusty pipe	JTMD	SV-15-1	KU-d12921	*Ectocarpus* sp.
5-Jan-13	Mosquito Creek dock	JTMD	M-5	KU-d12929	*Scytosiphon gracilis*
5-Jan-13	Mosquito Creek dock	JTMD	M-41	KU-d12916	*Bryopsis* cf. *plumosa*
6-Jan-13	Gleneden Beach boat	JTMD	SAL-1	KU-d12922	*Feldmannia mitchelliae*
29-Jan-13	Seaview rusty pipe	JTMD	LB-4	KU-d12923	*Alaria crassifolia*
1-Mar-13	Long Beach tire 4	JTMD	Cal-18	KU-d12918	*Chondrus yendoi*
12-May-14	Waldport panga	JTMD	WP-1	KU-d13965	*Ectocarpus* sp.
13-May-14	Waldport panga	JTMD	WP-2	KU-d13966	*Kuckuckia spinosa*
14-May-14	Waldport panga	JTMD	WP-3	KU-d13967	*Sphacelaria* sp.
15-May-14	Waldport panga	JTMD	WP-4	KU-d13968	*Petalonia fascia*
16-May-14	Waldport panga	JTMD	WP-5	KU-d13969	*Ulva simplex*
29-Apr-14	Lost Creek black float	JTMD	LC-1	KU-d13970	*Ulva* cf. *linza*
29-Apr-14	Lost Creek black float	JTMD	LC-2	KU-d13971	*Petalonia zosterifolia*
29-Apr-14	Lost Creek black float	JTMD	LC-3	KU-d13972	*Punctaria latifolia*
29-Apr-14	Lost Creek black float	JTMD	LC-4	KU-d13973	*Petalonia fascia*
26-Apr-14	Tillamook Wood	JTMD	TW-1	KU-d13974	*Polysiphonia morrowii*

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
19-May-14	North Cove	JTMD	NC-1	KU-d13975	*Scytosiphon lomentaria*
19-May-14	North Cove	JTMD	NC-2	KU-d13976	*Punctaria latifolia*
19-May-14	North Cove	JTMD	NC-3	KU-d13977	*Sphacelaria* sp.
19-May-14	North Cove	JTMD	NC-4	KU-d13978	*Ulva compressa*
19-May-14	North Cove	JTMD	NC-5	KU-d13979	*Ectocarpus crouaniorum*
	(yet to be determined but JTMD)	JTMD	S-293	KU-d13981	*Scytosiphon lomentaria*
8-Sep-14	Brighton Marina	OR	66	KU-d13325	*Petalonia fascia*
8-Sep-14	Jetty Fishery	OR	69	KU-d13326	*Petalonia fascia*
12-Aug-14	GH, jetty channel	WA	107	KU-d13327	*Petalonia fascia*
9/8/2014	Stackpole walk-out, Willapa Bay	WA	7	KU-d13328	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	13	KU-d13329	*Ectocarpus sp.*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	20	KU-d13330	*Ectocarpus* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	21	KU-d13331	*Ectocarpus* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	35	KU-d13332	*Ectocarpus* sp.
8-Sep-14	Grays Harbor SW	WA	41	KU-d13333	*Ectocarpus* sp.
8-Sep-14	Grays Harbor SW	WA	42	KU-d13334	*Ectocarpus* sp.
8-Sep-14	Grays Harbor SW	WA	43	KU-d13335	*Ectocarpus siliculosus*
12-Aug-14	GH, Brady's Oyster	WA	60	KU-d13336	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	11	KU-d13337	*Cladophora vagabunda*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	12	KU-d13338	*Cladophora oligocladoidea*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	14	KU-d13339	*Cladophora vagabunda*
8-Sep-14	Ilwaco docks	WA	82	KU-d13340	*Cladophora glomerata*
8-Sep-14	Grays Harbor SW	WA	36	KU-d13341	*Blidingia* sp.
8-Sep-14	Grays Harbor SW	WA	37	KU-d13342	*Gayralia oxysperma*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	24	KU-d13343	*Bryopsis* cf. *plumosa*
8-Sep-14	SW Shore	WA	47	KU-d13344	*Bryopsis* cf. *plumosa*
8-Sep-14	S-Bay Oyster	WA	48	KU-d13345	*Bryopsis* cf. *plumosa*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	19	KU-d13346	*Ulva compressa*
8-Sep-14	S-Bay Oyster	WA	49	KU-d13347	*Ulva* cf. *linza*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	27	KU-d13348	*Ulva* cf. *linza*
8-Sep-14	Grays Harbor SW	WA	39	KU-d13349	*Ulva compressa*
12-Aug-14	GH Jetty South	WA	93	KU-d13350	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	5	KU-d13351	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	18	KU-d13352	*Ulva compressa*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	26	KU-d13353	*Ulva compressa*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	23	KU-d13354	*Ulva compressa*
12-Aug-14	Brady's Oyster Farm	WA	58	KU-d13355	*Ulva lactuca*
12-Aug-14	Brady's Oyster Farm	WA	59	KU-d13356	*Ulva rigida/laetevirens*
8-Sep-14	Brighton Marina	OR	65	KU-d13357	*Ulva lactuca*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	15	KU-d13358	*Ulva* cf. *linza*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	25	KU-d13359	*Ulva* cf. *linza*
8-Sep-14	Grays Harbor SW	WA	38	KU-d13360	*Ulva compressa*
8-Sep-14	Grays Harbor SW	WA	44	KU-d13361	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	1	KU-d13362	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	10	KU-d13364	*Ulva* cf. *linza*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	29	KU-d13365	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
7-Sep-14	Stony Point Sands, Willapa Bay	WA	30	KU-d13366	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
7-Sep-14	Stony Point Sands, Willapa Bay	WA	31	KU-d13367	*Ulva* sp. 4 (in Ogawa *et al.* 2013)

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
8-Sep-14	S-Bay Oyster Farm	WA	50	KU-d13368	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	16	KU-d13369	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	17	KU-d13370	*Ulva* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	22	KU-d13371	*Ulva* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	28	KU-d13372	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
4-Jan-14	Long Beach	JTMD	108	KU-d13501	*Ectocarpus* sp.
4-Jan-15	Long Beach	JTMD	109	KU-d13502	*Ulva compressa*
20-Jan-15	Beverly Beach	JTMD	110	KU-d13503	*Punctaria latifolia*
20-Jan-15	Beverly Beach	JTMD	111	KU-d13504	*Scytosiphon* sp.
20-Jan-15	Beverly Beach	JTMD	112	KU-d13505	*Petalonia zosterifolia*
20-Jan-15	Beverly Beach	JTMD	113	KU-d13506	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	6	KU-d13559	*Callithamnion corymbosum*
12-Aug-14	Grays Harbor jetty - outside	WA	92	KU-d13560	*Grateloupia* sp.
14-Jul-10	Otter Crest	OR	119	KU-d13562	*Ptilota filicina*
17-May-10	Seal Rock	OR	120	KU-d13563	*Ptilota filicina*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	2	KU-d13564	*Ceramium pacificum*
8-Sep-14	Brighton	OR	63	KU-d13565	*Ceramium* sp.
12-Aug-14	Grays Harbor floating docks	WA	77	KU-d13567	*Ceramium* sp.
12-Aug-14	Grays Harbor floating docks	WA	80	KU-d13568	*Ceramium* sp.
12-Aug-14	Grays Harbor jetty - outside	WA	95	KU-d13569	*Ceramium pacificum*
12-Aug-14	Grays Harbor Jetty, channel	WA	102	KU-d13570	*Membranoptera platyphylla*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	32	KU-d13571	*Gracilaria vermiculophylla*
17-Jan-15	South Beach, inner jetty	OR	121	KU-d13572	*Gracilariopsis andersonii*
11-Jul-13	Lighthouse Point Beach, Cape Arago	WA	115	KU-d13574	*Ulva compressa*
11-Jul-13	Lighthouse Point Beach, Cape Arago	WA	116	KU-d13575	*Ectocarpus* sp.
11-Jul-13	Lighthouse Point Beach, Cape Arago	WA	117	KU-d13576	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	4	KU-d13580	*Neosiphonia harveyi*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	8	KU-d13581	*Neosiphonia harveyi*
8-Sep-14	Jetty Fishery	OR	67	KU-d13582	*Pterosiphonia bipinnata*
7-Sep-14	Oregon Shores	WA	52	KU-d13584	*Polysiphonia* sp.
8-Sep-14	Grays Harbor, SW	WA	40	KU-d13585	*Polysiphonia* sp.
12-Aug-14	Grays Harbor Jetty, outside	WA	96	KU-d13586	*Membranoptera platyphylla*
8-Sep-14	Grays Harbor, SW	WA	45	KU-d13587	*Hymenena flabelligera*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	34	KU-d13588	*Dasya baillouviana*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	3	KU-d13589	*Dasya baillouviana*
2-Mar-15	Manzanita, OR #1 - blue plastic basket	JTMD	125	KU-d13591	*Schizymenia dubyi*
2-Mar-15	Manzanita, OR #1 - blue plastic basket	JTMD	126	KU-d13592	*Ulva* cf. *linza*
2-Mar-15	Manzanita, OR #1 - blue plastic basket	JTMD	127	KU-d13593	*Petalonia fascia*
2-Mar-15	Manzanita, OR #2 - blue plastic basket	JTMD	128	KU-d13594	*Petalonia fascia*
2-Mar-15	Manzanita, OR #2 - blue plastic basket	JTMD	129	KU-d13595	*Polysiphonia morrowii*
2-Mar-15	Long Beach #9 -- white plastic tray	JTMD	130	KU-d13596	*Tsunamia transpacifica*
2-Mar-15	Long Beach #11 -- black buoy	JTMD	131	KU-d13597	*Ulva prolifera*
2-Mar-15	Long Beach #11 -- black buoy	JTMD	132	KU-d13598	*Ulva prolifera*
2-Mar-15	Long Beach #11 -- black buoy	JTMD	134	KU-d13600	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
2-Mar-15	Long Beach #11 -- black buoy	JTMD	135	KU-d13601	*Ectocarpus* sp.
	Grays Harbor Jetty	WA	158	KU-d13807	*Blidingia* sp.
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	201	KU-d13808	*Feldmannia mitchelliae*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	202	KU-d13809	*Ulva compressa*

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	203	KU-d13810	*Chondrus giganteus*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	204	KU-d13811	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	205	KU-d13812	*Petalonia fascia*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	206	KU-d13813	*Ulva pertusa/australis*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	207	KU-d13814	*Ulva compressa*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	208	KU-d13815	*Pyropia* sp.
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	209	KU-d13816	*Pyropia* sp.
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	210	KU-d13817	*Feldmannia mitchelliae*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	211	KU-d13818	*Ulva compressa*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	212	KU-d13819	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	213	KU-d13820	*Ectocarpus* sp.
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	214	KU-d13821	*Feldmannia mitchelliae*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	215	KU-d13822	*Petalonia fascia*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	216	KU-d13823	*Petalonia zosterifolia*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	217	KU-d13824	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	218	KU-d13825	*Punctaria latifolia*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	219	KU-d13826	*Punctaria latifolia*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	222	KU-d13828	*Feldmannia mitchelliae*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	223	KU-d13829	*Ectocarpus* sp.
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	225	KU-d13830	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	226	KU-d13831	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	228	KU-d13832	*Ulva compressa*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	229	KU-d13833	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	230	KU-d13834	*Ulva pertusa/australis*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	233	KU-d13836	*Ulva pertusa/australis*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	234	KU-d13837	*Ectocarpus* sp.
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	235	KU-d13838	*Feldmannia mitchelliae*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	237	KU-d13839	*Chondrus giganteus*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	238	KU-d13840	*Punctaria latifolia*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	239	KU-d13841	*Scytosiphon lomentaria*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	240	KU-d13842	*Ulva pertusa/australis*
Apr 9 or 10, 2015	Seal Rock Boat, off shore/SB marina	JTMD	244	KU-d13843	*Chondrus giganteus*
2-May-19	Long Beach dock fragment	JTMD	365	KU-d13844	*Blidingia minima*
2-May-19	Long Beach dock fragment	JTMD	367	KU-d13845	*Petalonia zosterifolia*
2-May-19	Long Beach dock fragment	JTMD	368	KU-d13846	*Bangia* sp.
2-May-19	Long Beach dock fragment	JTMD	369	KU-d13847	*Bangia* sp.
20-May-19	South Beach pilings	OR	370	KU-d13848	*Bangia* sp.
20-May-19	South Beach docks	OR	371	KU-d13849	*Grateloupia* sp.
20-May-19	South Beach docks	OR	372	KU-d13850	*Blidingia* sp.
20-May-19	South Beach docks	OR	373	KU-d13851	*Polysiphonia brodiei*
19-May-19	Boiler Bay	OR	374	KU-d13852	*Pylaiella washingtoniensis*
13-May-19	Seaview Boat 672	JTMD	375	KU-d13853	*Ulva compressa*
13-May-19	Seaview Boat 672	JTMD	376	KU-d13854	*Ulva compressa*
13-May-19	Seaview Boat 673	JTMD	377	KU-d13855	*Ulva compressa*
13-May-19	Seaview Boat 673	JTMD	378	KU-d13856	*Petalonia zosterifolia*
13-May-19	Seaview Boat 673	JTMD	379	KU-d13857	*Petalonia fascia*
13-May-19	Seaview Boat 673	JTMD	380	KU-d13858	*Petalonia zosterifolia*
13-May-19	Seaview Boat 674	JTMD	382	KU-d13860	*Scytosiphon lomentaria*

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
13-May-19	Seaview Boat 674	JTMD	383	KU-d13861	*Ectocarpus* sp.
13-May-19	Seaview Boat 676	JTMD	384	KU-d13862	*Ulva compressa*
13-May-19	Seaview Boat 676	JTMD	385	KU-d13863	*Ulva compressa*
13-May-19	Seaview Boat 677	JTMD	386	KU-d13864	*Petalonia zosterifolia*
13-May-19	Seaview Boat 679	JTMD	388	KU-d13866	*Petalonia fascia*
13-May-19	Seaview Boat 680	JTMD	389	KU-d13867	*Petalonia fascia*
4-Jan-15	Long Beach, black float	JTMD	399	KU-d13879	*Scytosiphon lomentaria*
4-Jan-15	Long Beach, black float	JTMD	404	KU-d13880	*Feldmannia irregularis*
4-Jan-15	Long Beach, black float	JTMD	405	KU-d13881	*Ectocarpus* sp.
9-Apr-15	Nye Beach Turnaround	JTMD	406	KU-d13882	*Ectocarpus* sp.
4-Jan-15	Long Beach, black float	JTMD	407	KU-d13883	*Feldmannia mitchelliae*
4-Jan-15	Long Beach, black float	JTMD	408	KU-d13884	*Feldmannia mitchelliae*
4-Jan-15	Long Beach, black float	JTMD	409	KU-d13885	*Scytosiphon lomentaria*
4-Jan-15	Long Beach, black float	JTMD	398	KU-d13899	*Ulva compressa*
25-Mar-15	Grays Harbor, oyster 3	WA	146	KU-d13995	*Bryopsis* cf. *plumosa*
26-Mar-15	GH, jetty channel	WA	157	KU-d13996	*Ulva californica*
26-Mar-15	GH, jetty channel	WA	158	KU-d13997	*Blidingia* sp.
27-Mar-15	GH, Westport docks	WA	159	KU-d13998	*Bryopsis* sp.
27-Mar-15	GH, Westport docks	WA	163	KU-d13999	*Ulva pertusa/australis*
27-Mar-15	GH, Westport docks	WA	165	KU-d14000	*Scytosiphon lomentaria*
28-Mar-15	WB, Port of Peninsula	WA	170	KU-d14002	*Blidingia* sp.
28-Mar-15	WB, Port of Peninsula	WA	172	KU-d14003	*Petalonia fascia*
27-Mar-15	GH, Westport docks	WA	177	KU-d14004	*Scytosiphon lomentaria*
27-Mar-15	GH, boat launch	WA	185	KU-d14006	*Gayralia oxyspermum*
28-Mar-15	WB, Port of Peninsula	WA	194	KU-d14008	*Bryopsis* sp.
17-Jun-15	Jetty Fishery	OR	249	KU-d14009	*Petalonia fascia*
17-Jun-15	Jetty Fishery	OR	251	KU-d14010	*Bryopsis* cf. *plumosa*
17-Jun-15	Brighton	OR	258	KU-d14011	*Petalonia fascia*
18-Jun-15	GH Jetty	WA	264	KU-d14012	*Blidingia minima*
18-Jun-15	GH Jetty	WA	265	KU-d14013	*Ulva lobata*
18-Jun-15	Brady's Oyster Farm	WA	266	KU-d14014	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
18-Jun-15	Brady's Oyster Farm	WA	267	KU-d14015	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
18-Jun-15	Brady's Oyster Farm	WA	270	KU-d14016	*Ulva torta*
19-Jun-15	S. Cove Oyster Farm	WA	281	KU-d14017	*Ulva lactuca*
19-Jun-15	S. Cove Oyster Farm	WA	282	KU-d14018	*Ulva* cf. *linza*
19-Jun-15	S. Cove Oyster Farm	WA	283	KU-d14019	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms	WA	287	KU-d14020	*Ulva lactuca*
20-Jun-15	N. Cove Oyster farms	WA	288	KU-d14021	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms	WA	289	KU-d14022	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms	WA	292	KU-d14023	*Bryopsis* sp.
20-Jun-15	N. Cove Oyster farms	WA	302	KU-d14025	*Ulva* cf. *linza*
20-Jun-15	N. Cove Oyster farms	WA	303	KU-d14026	*Ulva lactuca*
20-Jun-15	N. Cove Oyster farms	WA	304	KU-d14027	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms	WA	305	KU-d14028	*Cladophora albida*
20-Jun-15	N. Cove Oyster farms	WA	312	KU-d14030	*Ulva prolifera*
19-Jun-15	Westport docks	WA	314	KU-d14032	*Percursaria percursa*
19-Jun-15	Westport docks	WA	334	KU-d14033	*Ulva pertusa/australis*
19-Jun-15	Westport docks	WA	336	KU-d14034	*Ulva torta*

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
19-Jun-15	Westport docks	WA	337	KU-d14035	*Rosenvingiella radicans*
19-Jun-15	Westport docks	WA	338	KU-d14036	*Gayralia oxyspermum*
19-Jun-15	Westport docks	WA	339	KU-d14037	*Blidingia minima*
19-Jun-15	Westport docks	WA	340	KU-d14038	*Blidingia* sp.
17-Jun-15	Port of Peninsula	WA	353	KU-d14044	*Petalonia fascia*
17-Jun-15	Port of Peninsula	WA	354	KU-d14045	*Ulva pertusa/australis*
17-Jun-15	Port of Peninsula	WA	355	KU-d14046	*Cladophora vagabunda*
20-Jun-15	Ilwaco docks	WA	360	KU-d14048	*Blidingia* sp.
20-Jun-15	Ilwaco docks	WA	361	KU-d14050	*Ulva prolifera*
24-Mar-15	Grays Harbor, oyster2	WA	140	KU-d14214	*Ectcarpus siliculosus*
24-Mar-15	Grays Harbor, oyster2	WA	141	KU-d14215	*Pylaiella washingtoniensis*
24-Mar-15	Grays Harbor, oyster3	WA	142	KU-d14216	*Petalonia fascia*
24-Mar-15	Grays Harbor, oyster3	WA	145	KU-d14217	*Ectcarpus* sp.
24-Mar-15	Grays Harbor, oyster1	WA	150	KU-d14218	*Ectcarpus* sp.
27-Mar-15	Ilwaco	WA	173	KU-d14221	*Pylaiella* sp.
27-Mar-15	Ilwaco	WA	174	KU-d14222	*Pylaiella washingtoniensis*
16-Jun-15	Jetty Fishery	OR	255	KU-d14224	*Ectcarpus* sp.
17-Jun-15	GH Jetty	WA	262	KU-d14225	*Hincksia granulosa*
18-Jun-15	S. Cove Oyster Farm	WA	274	KU-d14226	*Ectcarpus* sp.
18-Jun-15	S. Cove Oyster Farm	WA	277	KU-d14228	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	297	KU-d14229	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	299	KU-d14230	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	300	KU-d14231	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	308	KU-d14232	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	309	KU-d14233	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm-drift	WA	6289	KU-d14234	*Alaria* sp.
18-Jun-15	Westport docks	WA	6275	KU-d14235	*Sargassum muticum*
16-Jun-15	Port of Peninsula	WA	351	KU-d14236	*Ectcarpus* sp.
2-Feb-16	South Beach Marina, Yaquina Bay	OR	493	KU-d14237	*Ulva pertusa/australis*
3-Feb-16	South Beach Marina pilings	OR	494	KU-d14238	*Blidingia* sp.
5-Jun-15	Agate Beach Dock	JTMD	436	KU-d16803	*Polysiphonia* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	625	KU-d16635	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	626	KU-d16634	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	627	KU-d16633	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	628	KU-d16625	*Polysiphonia* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	629	KU-d16628	*Polysiphonia* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	630	KU-d16638	*Petalonia fascia*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	631	KU-d16631	*Cladophora vagabunda*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	632	KU-d16632	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	633	KU-d16649	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	635	KU-d16648	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	636	KU-d16627	*Colaconema* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	638	KU-d16647	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	640	KU-d16645	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	641	KU-d16630	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	644	KU-d16644	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	645	KU-d16629	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	646	KU-d16640	*Ulva compressa*

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	647	KU-d16639	*Ulva compressa*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	648	KU-d16637	*Ulva compressa*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	651	KU-d16642	*Feldmannia mitchelliae*
28-Mar-16	Roads End derelict boat	JTMD	662	KU-d16688	*Petalonia fascia*
28-Mar-16	Roads End derelict boat	JTMD	663	KU-d16389	*Scytosiphon lomentaria*
28-Mar-16	Roads End derelict boat	JTMD	664	KU-d16689	*Petalonia zosterifolia*
28-Mar-16	Roads End derelict boat	JTMD	665	KU-d16699	*Ulva compressa*
28-Mar-16	Roads End derelict boat	JTMD	666	KU-d16700	*Ulva* cf. *prolifera*
28-Mar-16	Roads End derelict boat	JTMD	667	KU-d16701	*Ulva* cf. *prolifera*
28-Mar-16	Roads End derelict boat	JTMD	669	KU-d16710	*Colaconema* sp.
28-Mar-16	Roads End derelict boat	JTMD	674	KU-d16711	*Colaconema* sp.
28-Mar-16	Roads End derelict boat	JTMD	675	KU-d16705	*Polysiphonia morrowii*
28-Mar-16	Roads End derelict boat	JTMD	679	KU-d16703	*Sphacelaria rigidula*
28-Mar-16	Roads End derelict boat	JTMD	685	KU-d16713	*Feldmannia mitchelliae*
28-Mar-16	Roads End derelict boat	JTMD	686	KU-d16720	*Ectocarpus* sp.
28-Mar-16	Roads End derelict boat	JTMD	688	KU-d16714	*Feldmannia mitchelliae*
28-Mar-16	Roads End derelict boat	JTMD	689	KU-d16708	*Polysiphonia koreana*
28-Mar-16	Roads End derelict boat	JTMD	690	KU-d16721	*Ectocarpus* sp.
28-Mar-16	Roads End derelict boat	JTMD	691	KU-d16715	*Feldmannia mitchelliae*
28-Mar-16	Roads End derelict boat	JTMD	692	KU-d16690	*Punctaria latifolia*
28-Mar-16	Roads End derelict boat	JTMD	693	KU-d16716	*Feldmannia mitchelliae*
28-Mar-16	Roads End derelict boat	JTMD	694	KU-d16717	*Feldmannia mitchelliae*
28-Mar-16	Roads End derelict boat	JTMD	695	KU-d16723	*Ectocarpus* cf. *commensalis*
28-Mar-16	Roads End derelict boat	JTMD	697	KU-d16709	*Polysiphonia morrowii*
28-Mar-16	Roads End derelict boat	JTMD	698	KU-d16725	*Ectocarpus* cf. *commensalis*
28-Mar-16	Roads End derelict boat	JTMD	699	KU-d16726	*Ectocarpus* sp.
28-Mar-16	Roads End derelict boat	JTMD	700	KU-d16718	*Ectocarpus* sp.
28-Mar-16	Roads End derelict boat	JTMD	701	KU-d16691	*Petalonia zosterifolia*
28-Mar-16	Roads End derelict boat	JTMD	702	KU-d16698	*Cladophora* sp.
28-Mar-16	Roads End derelict boat	JTMD	703	KU-d16692	*Punctaria latifolia*
26-Mar-16	Forks derelict boat	JTMD	707	KU-d16727	*Ectocarpus* cf. *commensalis*
26-Mar-16	Forks derelict boat	JTMD	708	KU-d16693	*Scytosiphon lomentaria*
16-Apr-16	Sixes River derelict boat	JTMD	710	KU-d16663	*Grateloupia turuturu*
16-Apr-16	Sixes River derelict boat	JTMD	711	KU-d16659	*Cladophora albida*
16-Apr-16	Sixes River derelict boat	JTMD	712	KU-d16660	*Cladophora albida*
16-Apr-16	Sixes River derelict boat	JTMD	713	KU-d16683	*Sphacelaria rigidula*
16-Apr-16	Sixes River derelict boat	JTMD	714	KU-d16684	*Sphacelaria rigidula*
16-Apr-16	Sixes River derelict boat	JTMD	716	KU-d16657	*Mutimo cylindricus*
16-Apr-16	Sixes River derelict boat	JTMD	717	KU-d16667	*Blidingia minima*
16-Apr-16	Sixes River derelict boat	JTMD	718	KU-d16664	*Cryptopleura ruprechtiana*
16-Apr-16	Sixes River derelict boat	JTMD	719	KU-d16658	*Kuckuckia* sp.
16-Apr-16	Sixes River derelict boat	JTMD	721	KU-d16665	*Grateloupia turuturu*
16-Apr-16	Sixes River derelict boat	JTMD	722	KU-d16666	*Pyropia conwayae*
16-Apr-16	Sixes River derelict boat	JTMD	723	KU-d16685	*Sphacelaria rigidula*
16-Apr-16	Sixes River derelict boat	JTMD	724	KU-d16656	*Feldmannia mitchelliae*
16-Apr-16	Sixes River derelict boat	JTMD	726	KU-d16675	*Colaconema* sp.
16-Apr-16	Sixes River derelict boat	JTMD	727	KU-d16654	*Petalonia fascia*
16-Apr-16	Sixes River derelict boat	JTMD	728	KU-d16686	*Sphacelaria rigidula*

Appendix 10-1. List of JTMD and related specimens examined in genetic analyses (cont'd)

Date	Location (Source)	JTMD or other	Code by G.Hansen	Code in Kobe University dry specimens	Species identification
.	Otter Crest	OC	731	KU-d16668	*Blidiniga* sp.
	Otter Crest	OC	733	KU-d16670	*Blidiniga* sp.
	Otter Crest	OC	734	KU-d16676	*Polysiphonia* sp.
	Otter Crest	OC	735	KU-d16677	*Polysiphonia* sp.
		PP	747	KU-d16680	*Ulva pertusa/australis*
		PP	749	KU-d16661	*Cladophora opaca*
		PP	750	KU-d16662	*Cladophora opaca*
	Ilwaco	ILW	751	KU-d16681	*Ulva intestinalis*
	Ilwaco	ILW	752	KU-d16682	*Gayralia oxysperma*
28-Mar-16	Quail Street carboy	JTMD	620	KU-d16652	*Petroderma maculiforme*
26-Jul-16	Falcon Cove boat	JTMD	750	KU-d16662	*Ectocarpus* sp.
26-Jul-16	Falcon Cove boat	JTMD	751	KU-d16681	*Cladophora vagabunda*
26-Jul-16	Falcon Cove boat	JTMD	752	KU-d16682	*Ectocarpus* sp.
26-Jul-16	Falcon Cove boat	JTMD	753	KU-d16805	*Ectocarpus* sp.
5-Jun-12	Agate Beach Dock	JTMD	GIH5778	KU-d16804	*Analipus japonicus*
		OR	GIH4203		*Analipus japonicus*
5-Jun-12	Agate Beach Dock	JTMD	GIH5790a	KU-d15599	*Undaria pinnatifida*
5-Jun-12	Agate Beach Dock	JTMD	GIH5788	KU-d15600	*Costaria costata*
4-Jun-04	Boilger Bay	OR	GIH1932	KU-d15601	*Costaria costata*
9-Aug-06	N. Boaidmon	OR	GIH2787	KU-d15602	*Costaria costata*
24-Jun-98	Green Island	AK	98-pws-128	KU-d15603	*Costaria costata*
30-Oct-06	Tatoosh Island	WA	GIH2487	KU-d15604	*Alaria* sp.

JTMD = Japanese Tsunami Marine Debris, WA = Washington, OR = Oregon, AK = Alaska, OC = Otter Crest, ILW = Ilwaco

Robin Loznak


John Chapman

Chapter 11: Survival and fitness of Japanese Tsunami Marine Debris rafting species[1]

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Abstract

A high number of species survived the long transit through the North Pacific to arrive on the Pacific coast of North America with debris from the Great Japan Tsunami of 2011. We surveyed the settlement, growth history, size structure, and reproductive status of the more abundant Japanese Tsunami Marine Debris (JTMD) species to better understand factors that contributed to their successful oceanic transit. Because the Mediterranean mussel *Mytilus galloprovincialis* arrived on so many debris items in good condition, we used this coastal filter-feeding species as a model to explore size, reproduction, growth, and dispersal patterns of JTMD biota. Variations in size, growth rate, and reproductive state between arrivals in North America and Hawaii suggest that the drift path affected fitness during transit.

Non-native peracaridan crustaceans (including gammarid and caprellid amphipods, isopods, and tanaids) on drifting objects began to arrive on the Pacific shores of North America in June 2012 and continued through 2016. While many Asian species have survived the North Pacific transit on JTMD due to their long lives, short-lived species can only survive multi-year open ocean crossings on JTMD by self-recruitment. We surveyed peracaridan crustaceans from JTMD objects arriving on the Oregon and Washington coasts to assess their potential for self-replacement as well as their diversity, relative abundances and geographical origins. A diverse assemblage of short-lived peracaridan crustaceans capable of reproduction and self-recruitment in transit has continued to arrive with JTMD over the years of this study.

Introduction

The majority of biota associated with Japanese Tsunami Marine Debris (JTMD) arrived as adults. This characteristic is in contrast to other vectors known to successfully transport non-native species, such as ballast water, which typically involve early life stages, such as larvae. Therefore, one of our research priorities was to learn more about the settlement and growth history, size structure, and reproductive status of the more abundant JTMD species to better understand factors that contributed to their successful oceanic transit.

The Mediterranean mussel *Mytilus galloprovincialis* is a non-native species that is established in Japan and was common on JTMD, present on more than 50% of the items that we classified as JTMD. As this is a predominantly intertidal, filter-feeder species known to grow well in relatively warm and saline waters, it is noteworthy that so many individuals arrived in apparently good condition at relatively large sizes. Therefore, we used this coastal filter-feeding species as a model to explore size, reproduction, growth, and dispersal patterns of JTMD biota. To accomplish this, we determined the reproductive status and size frequency distributions of *M. galloprovincialis* arriving on 35 JTMD items (docks, pallets, totes, and skiffs) collected from 2012 to 2014. We also determined aspects of the growth and dispersal history of *M. galloprovincialis* on 17 of the JTMD items by completing structural and chemical analysis on the shells of representative mussels. The premise of this analysis relies on the fact that coastal waters typically display higher concentrations of certain trace metals, such as barium (Ba), than offshore, open ocean waters (Bruland, 1983; Murphy et al., 2008). Therefore, the hypothesis was that trace metal composition of the mussel shells could be used to identify shell growth that occurred in Japanese coastal waters (relatively high Ba), open ocean waters (relatively low Ba), and potentially U.S. coastal waters (relatively high Ba), if adequate shell growth occurred.

Short-lived peracaridan crustaceans survived ocean crossings on the same JTMD objects as the long-lived species. These small crustaceans survived by self-replacement. Knowledge of how these organisms completed entire life cycles during the open ocean crossings thus provides an additional foundation for assessing the risks of alien species. Populations of these crustaceans survived for multiple years on these drifting objects by self-recruitment. Potential for cross-recruitment among JTMD objects at sea would have been very low. This report includes analyses of peracaridan crustaceans collected from fouling assemblages on floating debris, such as docks, boats, pallets, household objects, baskets and trays that drifted across the Pacific Ocean from northern Japan to the west coast of the United States.

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[1] A reduced version of this chapter first appeared in PICES Press Vol. 24, No. 1, 2016. A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 60-69.


John Chapman

Methods

Growth, reproduction and dispersal history of mussels on JTMD

We collected and synthesized information on size and reproductive state of the mussel *Mytilus galloprovincialis* (hereafter called *Mytilus*) on JTMD items that had adequate numbers of individuals (>15) for analysis. Overall, we completed the size and reproduction assessment on over 1,000 individuals.

We conducted structural (growth) and chemical (Barium/Calcium) analyses on the *Mytilus* shells of a subset of individuals across an observed size range from representative debris items collected during the spring 2014 pulse of JTMD vessels. These data provide information on water mass residency (coastal vs. open ocean waters) and associated shell growth, which in turn provide key information on growth conditions experienced by different JTMD items and the duration of an item's residence in coastal waters. These efforts added to our relatively comprehensive picture of the size and growth of *Mytilus* arriving on selected JTMD items from June 2012 through June 2014.

For structural and chemical analysis, we prepared thin sections of the *Mytilus* shells and focused on the umbo region, which includes shell deposited throughout the life of each individual. We quantified the Ba/Ca pattern within the shells for a representative sample of individuals across the size distribution on selected JTMD items using laser ablation inductively-coupled plasma mass spectrometry.

Growth and survival of crustacean species

We assessed species abundances and population structure of peracardian crustaceans. In order to do this we sorted sample populations by reproductive development (juveniles and mature adults) and by sex and used image analyses to measure size and appendage lengths. We calibrated digital image measures by repeated measures, using a calibrated microscope and by redundant measures of the images. We surveyed the size frequencies and reproductive conditions of arriving peracaridan crustaceans to assess the ocean survival and invasion potential of short-lived JTMD species. We also analyzed the taxonomy of JTMD peracaridan crustaceans to partially measure the potential of JTMD as a mechanism for transporting unique Asian species to North America with the potential to establish new populations.

Results

Mussel size and reproduction

Based on 11 JTMD items, the size class distributions of initial mussel arrivals were normally distributed, which indicated that these JTMD items were likely colonized with biota prior to the tsunami. However, mussels arriving on later JTMD items displayed truncated or skewed size distributions (Figure 11-1). This observation, in conjunction with the occurrence of JTMD items from northern Japan that were arriving with species found only in more southerly locations and the collection of terrestrial origin debris colonized with *M. galloprovincialis* and other Japanese biota, indicated that at least some biota settled on these items after the tsunami.

From 2012 to 2013, the mean size of *Mytilus* increased by 10 to 19 mm yr^{-1} on items arriving in Oregon and Washington but not in Hawaii (Figure 11-2), suggesting that at least some portion of the biofouling community on JTMD items traveling in more northerly waters continue to grow two or more years after the tsunami. However, in 2014 there was no observed increased in size of *Mytilus* collected in Oregon and Washington. Furthermore, reproductive individuals consistently arrived throughout our collections from 2012 to 2014. The mean proportion of reproductive individuals was lowest in Hawaii (0.164, $p < 0.1$), intermediate in Washington (0.608) and greatest in Oregon (0.693). The proportional difference between Washington and Oregon was marginally significant ($p = 0.05$). Therefore, reproductive individuals may have released gametes along the Northeast Pacific (Oregon and Washington) coast (Figure 11-3).

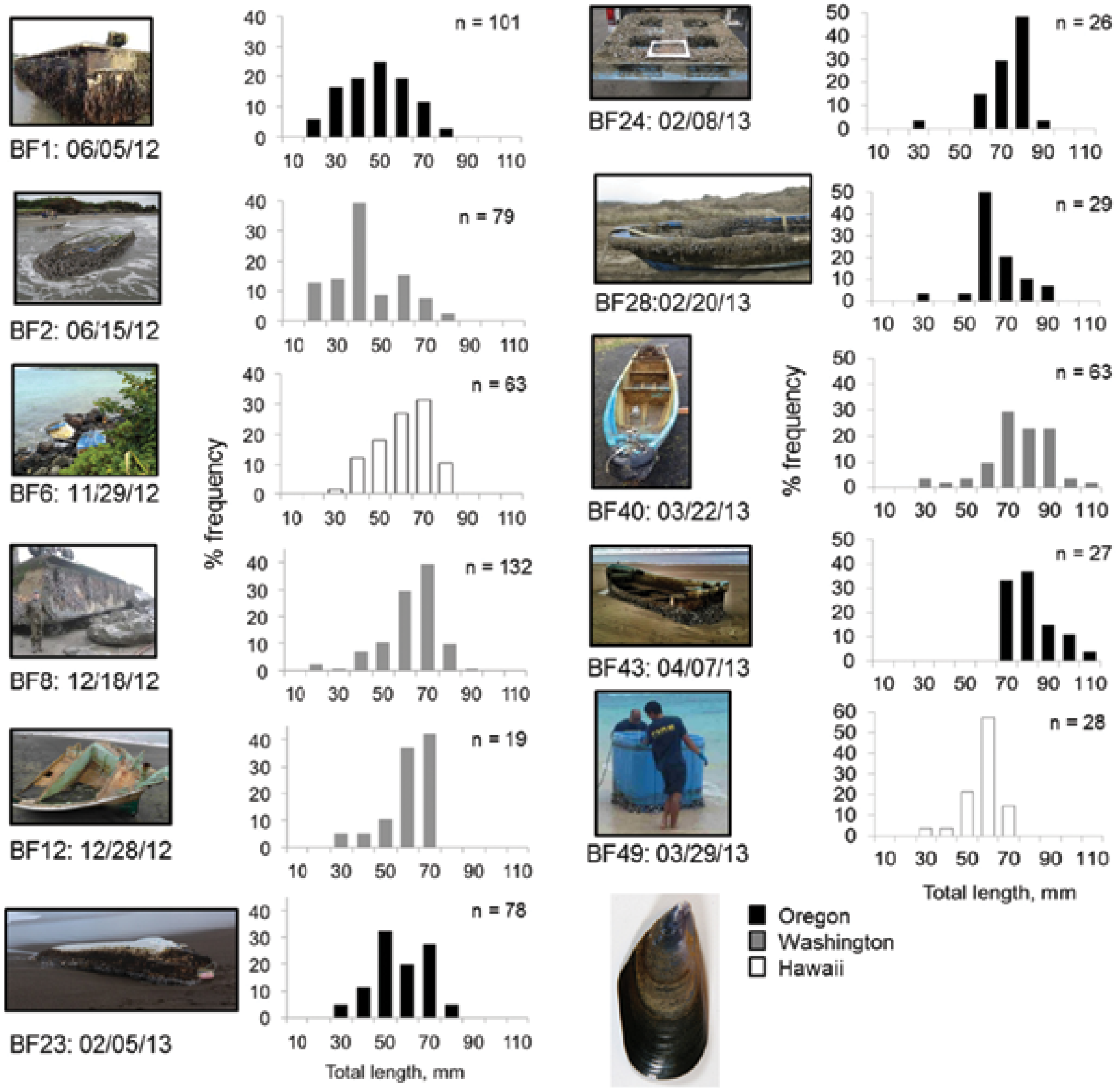
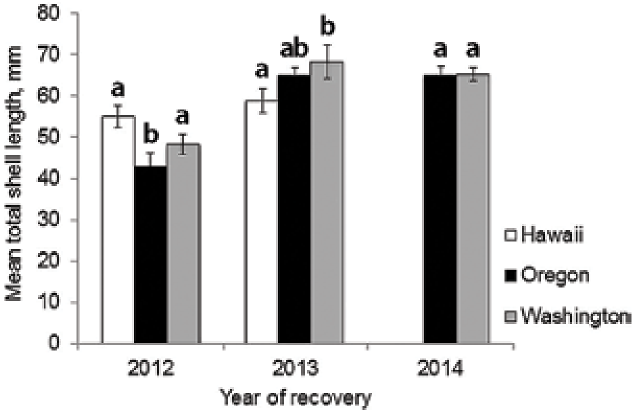


Figure 11-1. Size frequency distribution for total shell length (mm) of *Mytilus* sp. on JTMD items. Each sampled item was given a unique identification (BF1, etc). The estimated date of item arrival on a local beach is included along with sample size for each item.

Figure 11-2. Mean length (±2 SE) of *Mytilus* recovered on JTMD. Letters indicate groups that are statistically similar within years. Across years, *Mytilus* from Hawaii were equivalent in size in 2012 and 2013 whereas Oregon and Washington samples increased in size in 2013, compared with 2012, but then stabilized. Washington samples were larger than Oregon and Hawaii in 2012 and 2013 but not 2014. Total $n = 1{,}067$.



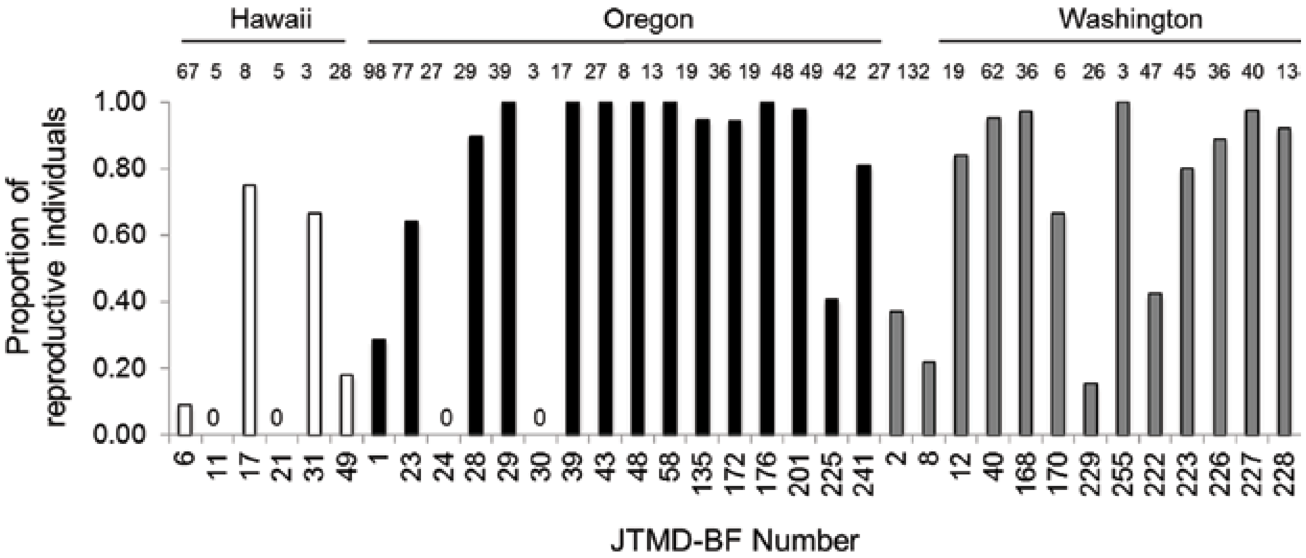


Figure 11-3. Proportion of *Mytilus* with mature or maturing gametes on various JTMD-BF items recovered in Hawaii, Oregon, and Washington. Sample sizes are included at top of graph. JTMD-BF numbers are along the *x*-axis and are arranged chronologically within each region with the earliest recoveries (2012) on the left.

Growth and dispersal history of mussels on JTMD

We observed the hypothesized pattern of elevated Ba/Ca during presumed residence in coastal waters of the Northeast Pacific (Figure 11-4). The patterns of shell Ba/Ca were remarkably consistent within individuals of similar sizes on the same JTMD item. Interestingly, for earlier JTMD items, we detected a peak in Ba/Ca (usually >2x background levels observed during presumed oceanic transport), followed by a period of low Ba/Ca (presumed oceanic transport), and finally a gradual elevation of Ba/Ca at the outer shell edge. Although peaks in bivalve shell Ba/Ca have been observed in several taxa, the causes of these peaks remain unclear. Potential hypotheses include consumption of large amounts of senescent phytoplankton post-bloom and/or the consumption of barite particles (Gillikin et al., 2008; Thebault et al., 2009). However, background water Ba/Ca is well-correlated with water Ba/Ca levels. In this instance, it is possible that the peaks observed in some of the JTMD *Mytilus* were directly related to the tsunami. The tsunami was associated with the delivery of a tremendous amount of Ba-rich terrestrial sediments and debris into the coastal zone, the disturbance of large regions of high-Ba pore water, and potentially facilitated an enhanced spring bloom in northwestern Pacific coastal waters off Japan.

Based on the Ba/Ca profiles, we separated shell growth into two categories:

1. "Oceanic growth" identified as shell growth during periods of low Ba/Ca after the earlier Ba/Ca peak, if present, and
2. "Growth in Northeast Pacific coastal waters" identified as the region with gradual increase in Ba/Ca at the outer edge of each shell.

Mytilus galloprovincialis

Amy Green

In order to assess growth in Northeast Pacific coastal waters, we estimated the total shell length at the point where Ba/Ca levels began to increase at the outer edge, i.e, when mussels entered coastal waters of the Northeast Pacific Ocean, based on back-calculation models of umbo width and total shell length ($R^2 > 0.75$) (Figure 11-4). This allowed us to estimate total shell deposition during residence in coastal waters of the Northeast Pacific (i.e., shell deposition during the gradually increasing shell Ba/Ca at the outer shell edge). As we have no specific estimates of days of coastal residency, these growth values are presented as total shell deposition. Overall, mussels displayed variable shell growth during coastal residency in the Northeast Pacific (Figure 11-5), which indicates that the duration of residence in coastal waters along the Pacific North America varied across JTMD items.

We also estimated total growth based on mussel shell size upon landing and time since the tsunami. The JTMD mussels grew, on average, 0.075 ± 0.018 SE mm day^{-1} during transit with a notable decline for mussels that landed in 2014, three years after the tsunami. Therefore, although slower than growth rates attained in coastal locations or culture settings (~0.12–0.16 mm day^{-1}) (Peteiro et al., 2006; Cubillo et al., 2012), the JTMD mussels were growing during their oceanic transit and arrived in many locations capable of reproduction after 15 to 40+ months at sea.

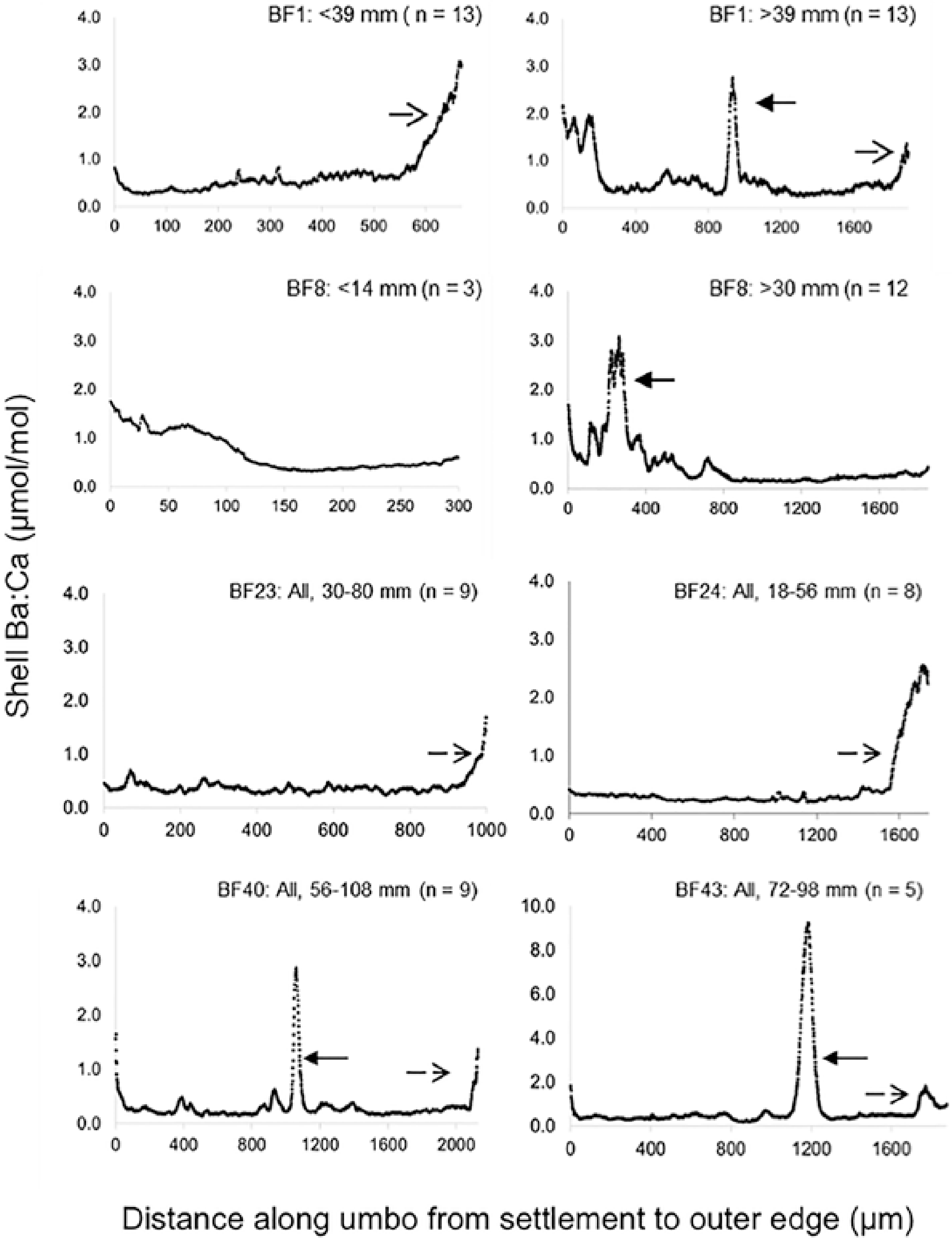


Figure 11-4. Representative Ba/Ca profiles across the umbo growth axis for *Mytilus* from selected JTMD-BF items. Note for BF1 (Misawa Dock 1), BF2 (skiff), and BF8 (Misawa Dock 3), the smaller shells do not display any peak in shell Ba/Ca prior to the gradual increase at the outer shell edge. The solid arrow indicates the initial Ba/Ca peak that is interpreted as occurring in the northwestern Pacific, potentially related to the tsunami, and the open arrow is interpreted as arrival in Pacific coastal waters of North America.

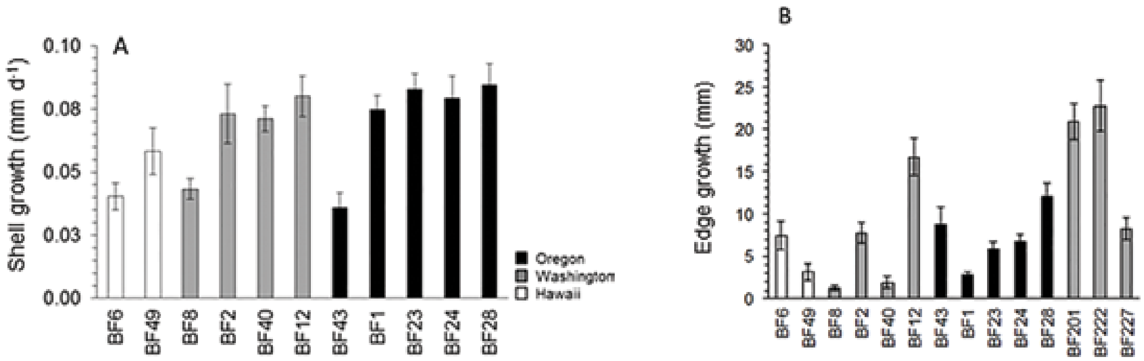


Figure 11-5. (A) Mean (±2 SE) shell growth of *Mytilus*. (B) The estimated growth for JTMD *Mytilus* on the items identified in (A) and three additional JTMD items collected in spring 2014. Edge growth estimates represent total shell deposition during periods with moderately elevated Ba/Ca, presumably indicative of Northeast Pacific coastal waters.

Table 11-1. North Pacific distributions and biogeographic distribution of peracaridan crustaceans arriving on JTMD with previous records in upper case X indicating accepted names, lower case x indicating uncertain taxonomic status of the sampled populations and red font indicating new records for the Pacific coast of North America.

	Species	**JTMD**	**Japan**	**Hawaii**	**Pacific North America**	**Global**
Amphipoda	*Allorchestes angusta*	X		X	X	
	Ampithoe koreana	X	X			
	Ampithoe lacertosa	X		X	X	
	Ampithoe valida	X	X	X	X	X
	Gammaropsis japonica	X				
	Jassa carltoni	x			x	
	Jassa marmorata	X	X	X	X	
	Jassa slatteryi	x	x	x	x	
	Jassa staudei	x	x	x	x	
	Stenothoe crenulata	X				X
	Stenothoe dentirama	x				
	Stenothoe gallensis	x		x		X
	Caprella cristibrachium	X	X			
	Caprella equilibra	X	X		X	X
	Caprella mutica	X	X		X	
	Caprella penantis	X	X		X	X
	Caprella verrucosa	X			X	X
Tanaidacea	*Zeuxo normani*	X	X	X	X	X
Isopoda	*Dynoides spinipodus*	X	X			
	Ianiropsis derjugini	X				
	Ianiropsis serricaudis	X			X	X
	Munna japonica	X				

Crustacean species associated with JTMD

We identified 17 amphipod species, one tanaidacean species and four isopod species from JTMD (Table 11-1). Four of the amphipod species, *Ampithoe koreana, Stenothoe crenulatta, Caprella cristibrachium* and *Gammaropsis japonica,* and two isopod species, *Dynoides spinipodus* and *Munna japonica* (*Munna japonica* recognized from a low quality specimen) are new records for North America (Table 11-1). We assigned the known Northeast Pacific ranges to 13 of the 22 species identified.

Single specimens from individual objects were unsuited for size analyses. However, we did not find large populations lacking in either juveniles or reproductive adults. The size frequencies of these crustaceans revealed multiple overlapping cohorts within sexes (Figure 11-6). Recent trophic conditions surrounding the JTMD objects thus appear to have been suitable for long-term persistence but variable. For example, the greater frequencies of small or juvenile amphipods on item BF-23 (a Japanese vessel that landed in Oregon in February 2013) than on BF-40 (a vessel that landed in Washington in March 2013) indicate that the recent history of BF-23 included less time in high trophic availability conditions than BF-40 (Figure 11-6).

Although size frequencies and reproductive stages varied, all populations were reproductive. We did not find any mature but non-reproductive peracaridan populations. Peracaridan crustaceans could have restricted reproduction and survival on most JTMD objects and populations surviving ocean crossing could have had high potential to invade North American ecosystems.

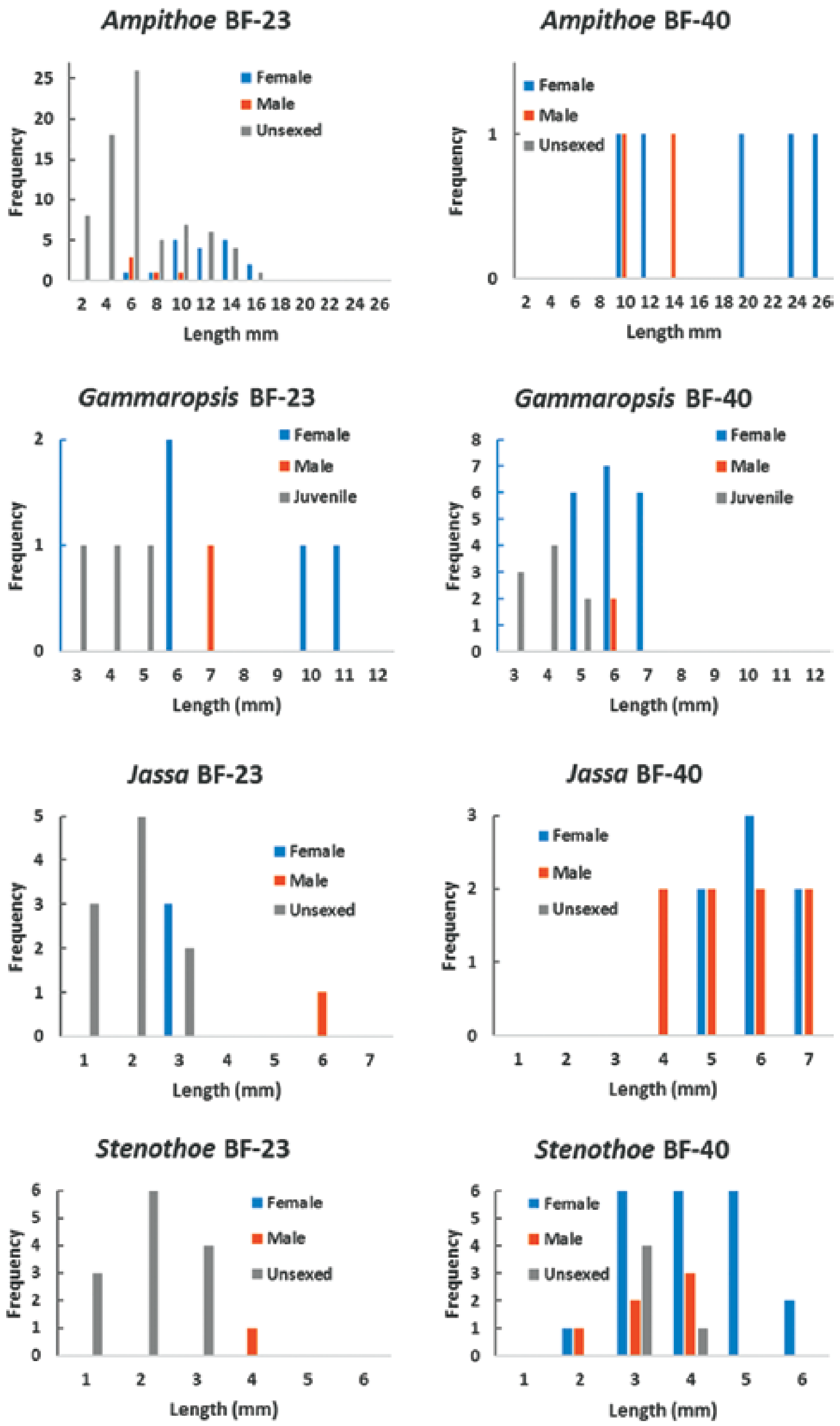


Figure 11-6. Length frequencies of male, female and juvenile *Ampithoe*, *Gammaropsis*, *Jassa* and *Stenothoe* from JTMD objects BF-23 and BF-40.

Discussion

In summary, we used the Mediterranean mussel *Mytilus galloprovincialis* to provide information on the settlement and growth history of biota successfully transported across the Pacific on debris generated from the Great Japan Tsunami of 2011. Although there is much we do not yet know about the JTMD biota, detailed examination of certain common species can provide novel insights on JTMD as a transport vector and aid efforts to evaluate the potential risks associated with its arrival in the Pacific coastal waters of the U.S. and Canada.

The absence of peracaridan crustaceans on natural JTMD objects (including trees) is in contrast to their numerous and frequent occurrences on artificial, anthropogenic objects. Their greatest abundances and highest densities were on the largest artificial objects. Reproductive individuals of all peracaridan species that arrived on Pacific North American shores with JTMD undoubtedly escaped into the receiving environments. Evidence that these individuals contributed to the establishment of reproductive populations subsequently is lacking. The geographical mixture of these morphotypes and genotypes suggests that the interactions of these cryptic species allow long-term coexistence on artificial substrates. Of the peracaridan species recovered from JTMD, *Ampithoe koreana, Stenothoe crenulatta, Caprella cristibrachium, Gammaropsis japonica, Dynoides spinipodus* and *Munna japonica* (recognized from a poor quality specimen) are new North American records.

This research established that a diverse assemblage of short-lived peracaridan crustaceans capable of reproduction and self-recruitment in transit has continued to arrive with JTMD over the years of this study. These self-sustaining JTMD species have potentially longer half-lives of invasion risk for North American communities than the long-lived JTMD species.

Acknowledgements

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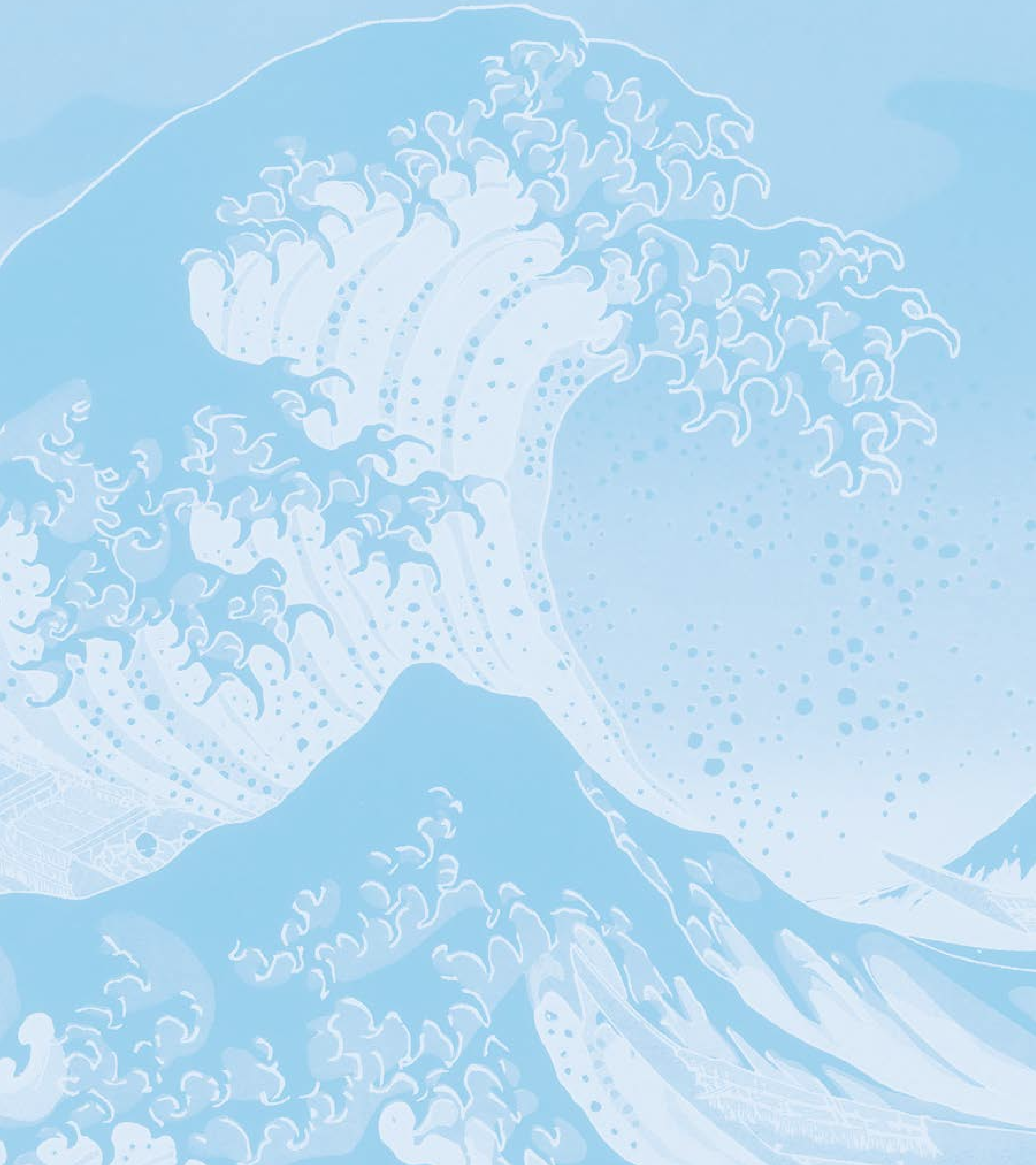

Washington Department of Fish and Wildlife

Chapter 12: Distributional, environmental, and life history attributes of Japanese Tsunami Marine Debris biota[1]

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Abstract

Nearly 380 species of algae, invertebrates, and fish have been transported thousands of kilometers on Japanese Tsunami Marine Debris (JTMD). While it is now evident that drifting debris can successfully transport marine species across the Pacific Ocean, there is a lack of information on the life history, environmental, and distributional characteristics of these JTMD species. The ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project supported the development of a database of distributional, environmental, and life history information for many of the JTMD species. We modified that database to: (1) quantify variability in attributes of JTMD coastal invertebrate species along statistically independent gradients using non-metric multidimensional scaling analysis and (2) compare traits of JTMD species with known invasion histories to remaining JTMD species. We synthesized life history, environmental, and distributional information for 103 of the JTMD species and compared traits of species with ($n = 30$) and without ($n = 62$) known invasion histories to determine which, if any, traits differentiated between species in these two groups. The species represent 12 phyla, and Mollusca, Crustacea, and Bryozoa accounted for 71 of the 103 species. The majority are native to the Northwest Pacific and the Central Indo-Pacific. Trait analysis discriminated species with known invasion histories from those with no such history. Species with a known invasion history were more common on artificial and hardpan substrates, in temperate reef, fouling, and flotsam habitats, at subtropical and tropical temperatures, and exhibited greater salinity tolerance than species with no prior invasion history. Thirty-five JTMD species without prior invasion history overlapped in ordination trait space with known invaders, indicating a subset of species in this novel assemblage that possess traits similar to species with known invasion history.

Introduction

In the six years since the devastating Great Japan Tsunami of 2011, it has become evident that, in addition to a myriad of social, economic, and environmental concerns associated with the tragedy, hundreds of coastal species from Japan have crossed the Pacific Ocean associated with tsunami debris. As of January 2017, we documented the arrival of over 630 debris items, including docks, buoys, boats, pallets, and wooden structures. All of these items were identified as Japanese Tsunami Marine Debris (JTMD) based on evidence as presented in Chapter 7.

A monumental effort by many researchers and taxonomists has generated a comprehensive list of species associated with JTMD. Nearly 380 taxa have been collected on JTMD that landed on the Pacific coast of North America and in the Hawaiian Archipelago since 2012 (Choong et al., 2012; Calder et al., 2014; Carlton et al., 2017). While the movement of marine species around the globe through anthropogenic activities, such as ballast water and hull fouling, has been a concern for some time (Carlton and Geller, 1993; Carlton, 1996; Ruiz et al., 1997; Callaway et al., 2006), the transport of such large numbers of marine species across ocean basins via massive amounts of marine and terrestrial debris appears to be a new phenomenon that has not yet been well documented.

JTMD has certain unique attributes in comparison with other known marine vectors, such as ship hull fouling and ballast water (Sylvester et al., 2011; Clarke Murray et al., 2012; Lo et al., 2012). Ships arrive in known locations and at measurable frequencies whereas JTMD, which is propelled by winds and currents and thus travels at much slower speeds than ships, can arrive almost anywhere at any time – arguably the most stochastic transport vector yet described. Due to the slow rates of transport by currents rather than propulsion, the effects of drag and dislodgement were

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[1] A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 90-101.


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substantially reduced on JTMD compared to ship hull fouling (Clarke Murray et al., 2012). Furthermore, JTMD transports large numbers of adults, similar to hull fouling, rather than larval stages that are more common in ballast water (Ruiz and Carlton, 2003).

As of January 2017, only one JTMD species, the striped beakfish *Oplegnathus fasciatus*, had been observed free-living along the west coast of North America (in Oregon and Washington). At this time, we do not know if any of these JTMD species will become established outside of their current distributional range as a result of the earthquake and tsunami. As part of an international effort to evaluate the potential impacts from JTMD and associated species, a database of life history, distributional, and environmental attributes of many JTMD species was developed for reference and analysis.

In addition, we had a unique opportunity to examine those species that arrived on JTMD in greater detail in order to increase our understanding of transoceanic dispersal of coastal species. We modified the JTMD database to focus on attributes with broad coverage across species in order to: (1) quantify variability in attributes along statistically independent gradients and (2) compare traits of JTMD species with known invasion histories to remaining JTMD species. The work contributes to the synthesis goals of the ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project, provides a qualitative and quantitative evaluation of JTMD species attributes, and identifies attributes that distinguish JTMD species with known invasion histories from those with no prior invasion history.

Methods

Species associated with JTMD

We considered a debris item as JTMD if it had:

1. Clear identification such as a serial or registration number that was linked to an object lost during the tsunami of 2011,
2. Clear evidence of associated biota originating primarily from the Tohoku coast of Japan, which is where the greatest impacts from the tsunami occurred, or
3. A combination of these factors (Carlton et al., 2017).

JTMD biofouled items landing along the Pacific coast of North America (British Columbia, Canada and Alaska, Washington, Oregon, and California, USA) and the Hawaiian Archipelago were opportunistically sampled for algae, invertebrates, and fish between June 2012 and July 2016. Associated biota were collected, preserved, and identified to the lowest taxonomic level by experienced systematists. We used the publically accessible database of life history, distributional, and environmental traits of JTMD taxa that were identified to the species level[2]. The information came from a variety of sources, including primary publications, reports, databases, and internet searches in international literature, including Japanese.

For this analysis, we used the subset of invertebrate species for which there was adequate information for qualitative synthesis (Appendix 12-1; n = 103) and quantitative analysis (n = 92). Although 51 species (out of 154 species included in the database as of June 2016) were removed due to inadequate information, there was no difference in the proportion of species per phyla between the reduced (n = 103) and the larger (n = 154) database ($\chi^2 = 9.56$, df = 11, $P > 0.80$). In only two instances, we included a species complex (*Jassa marmorata*-complex and *Stenothoe crenulata*-complex).

We assigned each species to one of the three following invasion history categories:

1. Clear invasion history outside of native range with documented establishment in non-native areas,
2. Not known outside of its native range, or
3. Cryptogenic, i.e., unknown or unclear origin.

For 29 of the 30 species included in our analysis as having clear invasion history (Appendix 12-1), there is documentation of negative impacts on a novel environment outside of the species' native distribution. The history of one species, *Lyrodus takanoshimensis*, a wood boring bivalve, was somewhat ambiguous. It was identified as invasive by Carlton (1992) and as a probable invasive in Fofonoff et al. (2016). Therefore, given the available information, we included it as a species with a known invasion history in our analysis.

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[2] http://invasions.si.edu/nemesis/jtmd/index.jsp


Ocean Legacy

Qualitative synthesis

We compiled summaries of JTMD species across various categories of interest, including phyla, native range, and invasion history to provide some synthesis of the 103 species included in our analysis. Given that JTMD is arguably a newly documented species transport vector (Carlton et al., 2017), we also summarized the available information on previously reported transport history for these 103 species. Potential vectors included hull fouling, aquaculture and fisheries, ballast water, natural dispersal, recreation, moveable structures, solid ballast, and other (primarily natural dispersal). Given that we did not have robust estimates of species abundance or a comprehensive evaluation of which individuals were reproductive across debris items, we did not include any measure of abundance or propagule pressure. The number of species considered in each qualitative summary varied depending on the availability of information.

Quantitative analysis

Given that our objective was to quantitatively compare species with and without known invasion history, we removed the five cryptogenic species and six additional species with insufficient database coverage, which left 92 species in the subsequent analyses (Appendix 12-1). We used 14 variables, hereafter referred to as "traits", including the species' native marine realm and region (Spalding et al., 2007), temperature and salinity ranges, reproductive and developmental characteristics, mobility, habitats, and trophic status (Appendix 12-2). The database variables were transformed into binary or numerical data for analysis.

First, we characterized trait variation within the JTMD species pool using Nonmetric Multidimensional Scaling (NMS), which is an ordination technique based on ranked distances between species. Second, we tested the hypothesis that there were significant differences in traits between species with and without a known invasion history using a Multi-Response Permutation Procedure (MRPP). Third, we completed an Indicator "Species" Analysis (ISA) to identify traits that were responsible for group separation when identified using the MRPP. Finally, we identified the JTMD species with no invasion history that overlapped in ordination trait space with JTMD species with a known invasion history as a way to prioritize species for evaluation and monitoring.

Nonmetric Multidimensional Scaling (NMS) is an iterative process to rank and place *n* entities on *k* dimensions (axes) that minimize the stress of the *k*-dimensional configuration (McCune and Mefford, 2015). A measure of "stress", which has values between 0 and 100 (Kruskal, 1964; Mather, 1976), was determined; stress indicates the departure from monotonicity in the relationship between the dissimilarity (distance) in the original *p*-dimensional space and distance in the reduced *k*-dimensional ordination space. We completed two NMS ordinations using Euclidean distance measures with no penalty on handling ties. First, we used only the geographic distribution information (realm and region). Second, we used only the environmental and life history traits (Appendix 12-2). We adopted this approach because species with invasion histories may have disjointed geographic distributions that could influence the separation of groups in what could be considered a biased manner. Given that we were also interested in the variation in environmental and life history traits independent of geographic distribution, we completed separate analyses. For each ordination, a random starting configuration was used, and 500 iterations were run (200 with real data and 250 with randomized data) with 15 iterations to evaluate model stability based on a stability criterion of 0.000001. Pearson correlation analysis was used to examine the relationships between NMS axis scores and distributional, environmental, and life history traits, which provide information on the distribution of traits along axes. A conservative approach for the correlation analyses was adopted, and *P*-values were adjusted for multiple comparisons across traits using the Bonferroni correction.

We then evaluated the hypothesis that there were significant differences between species with and without invasion history using MRPP, which generates a weighted mean within-group distance (δ) and a chance-corrected within group agreement test statistic (A). We used the Euclidean distance measure as in the NMS. The probability of the observed δ given the expected δ is estimated based on an approximate distribution of δ using a continuous Pearson type III distribution, which incorporates the mean, standard deviation, and skewness of δ under the null hypothesis of no difference between groups (Mielke and Berry, 2007). MRPP is a non-parametric procedure somewhat analogous to discriminant analysis except that it does not require certain assumptions, such as multivariate normality and homogeneity of variances.

We followed the MRPP with ISA to determine which traits were statistically different in species with and without known invasion history. ISA generates Indicator Values (IVs) based on the proportional abundance and frequency of occurrence of a species, or trait in this instance, for each pre-defined group. Statistical significance of IVs, which range from 0 (no group indication) to 100 (perfect group indication), was determined based on Monte Carlo tests with 5,000 permutations to generate random IVs for comparison with observed IVs.

NMS decomposes the species *x* trait database into orthogonal axes of variation and each species is assigned a position in multivariate space (i.e., an Axis 1, 2, and 3 value). Therefore, we identified those JTMD species with no invasion history that overlapped in ordination space with species with an invasion history. In other words, we removed species with no invasion history that did not overlap in at least one dimension with species with known invasion history. All analyses were completed using PC-ORD 7.0.

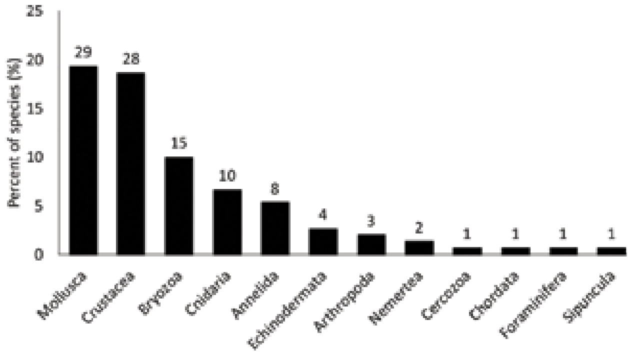

Figure 12-1. The percent of JTMD species per phylum (*n* = 103 species). The number of species per phylum is given above each bar.

Results

Species associated with JTMD

The 103 JTMD species represent 12 phyla with Mollusca, Crustacea, and Bryozoa accounting for 71 of the 103 species included in this analysis (Figure 12-1). Four phyla (Cercozoa, Chordata, Foraminifera, and Sipuncula) were each represented by one species.

Qualitative synthesis

The reported native realm for the 103 JTMD species covers the globe (Figure 12-2), with species ranging from the Southern Ocean (hydrozoan *Halecium tenellum*) to the Arctic (bryozoan *Callopora craticula*). However, the majority (>70%) are native to the temperate Northwest Pacific and the Central Indo-Pacific. The majority of species had no invasion history (*n* = 68), while nearly a third had a known invasion history (*n* = 30), and a few were cryptogenic (*n* = 5) (Appendix 12-1). Eight transport categories were documented, and the largest number of species (30) was reported as hull fouling, followed by transport through aquaculture and fisheries activities and ballast water (Figure 12-3).

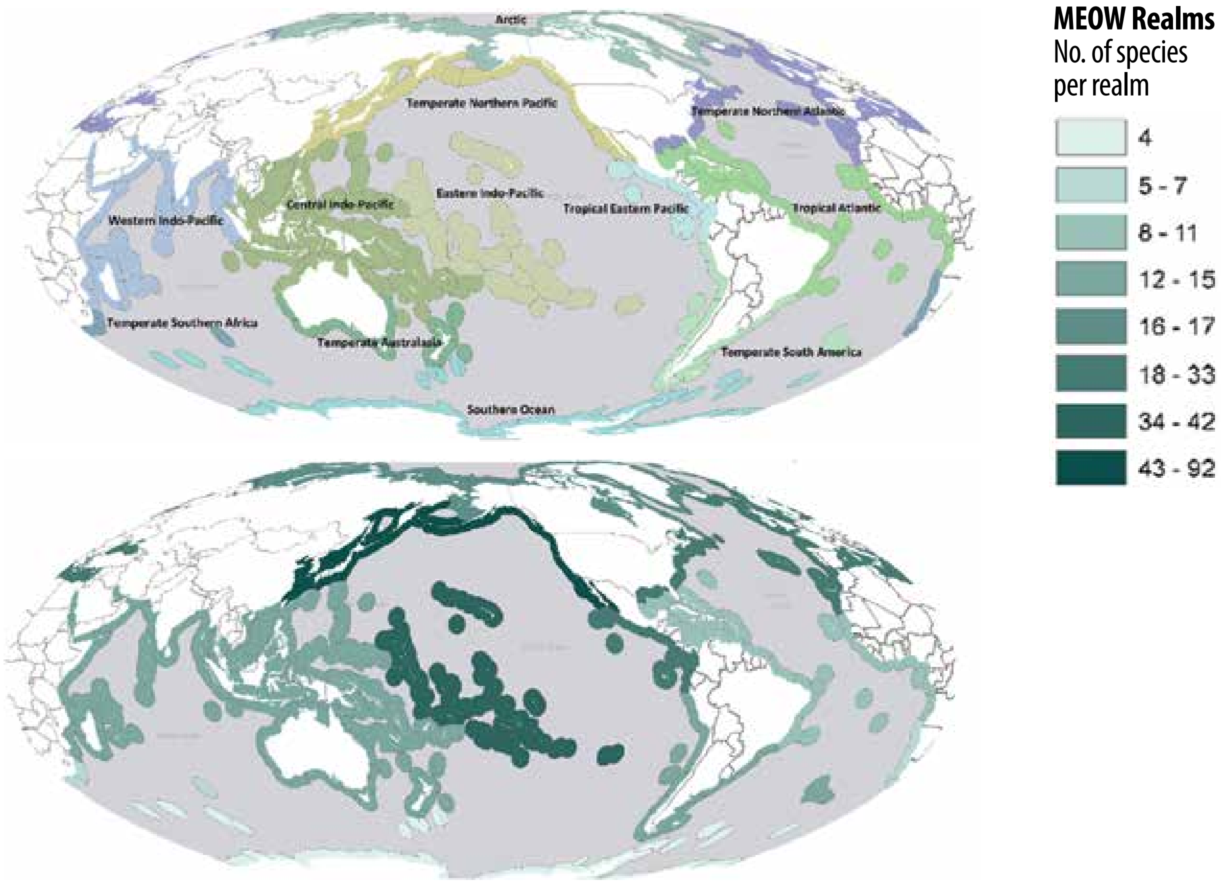

Figure 12-2. The 12 marine realms, which are from the Marine Ecoregions of the World (MEOW) (Spalding et al., 2007), used to characterize the native distributions of Japanese Tsunami Marine Debris (JTMD) species (left). The number of JTMD species reported per native realm (right). A species can be present in multiple realms. See Appendix 12-2 for details on the realms of origin.

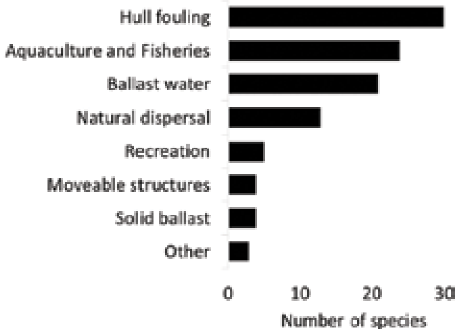

Figure 12-3. The number of JTMD species documented per transport vector; each species can be reported under multiple vectors. A total of 45 species of 104 total have been documented on a vector, including 30 of the 31 species with known invasion history, 3 of the 4 cryptogenic species, and 12 that were documented on a vector but have no invasion history (which were mostly natural dispersal).

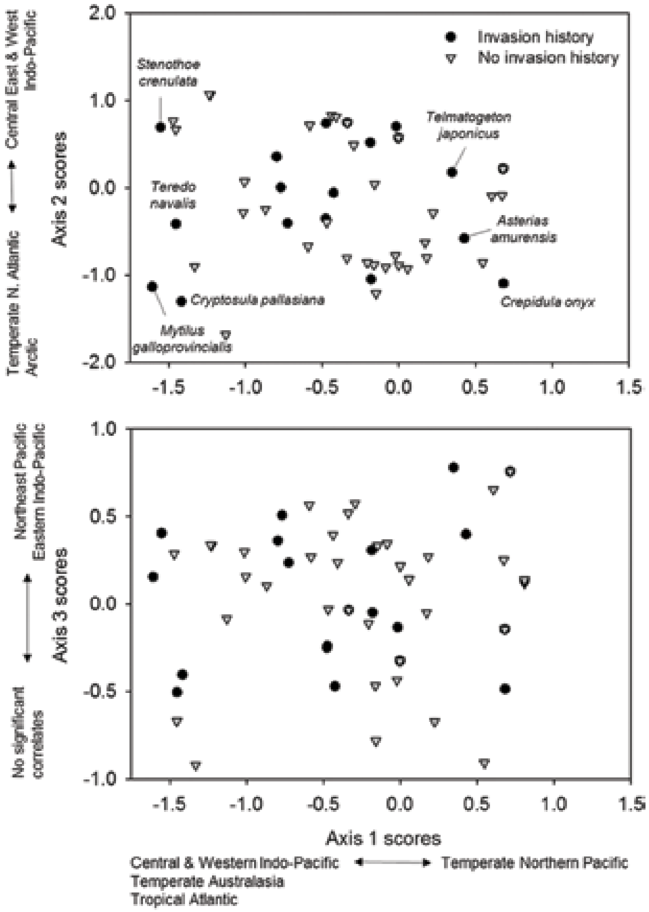

Figure 12-4. Ordination of 92 JTMD species with known (black filled circles) or no invasion history (grey filled triangles) based on reported geographic distribution. Realms or regions that were significantly correlated with axis scores are included along each axis. Selected species known to be invasive are identified for reference.

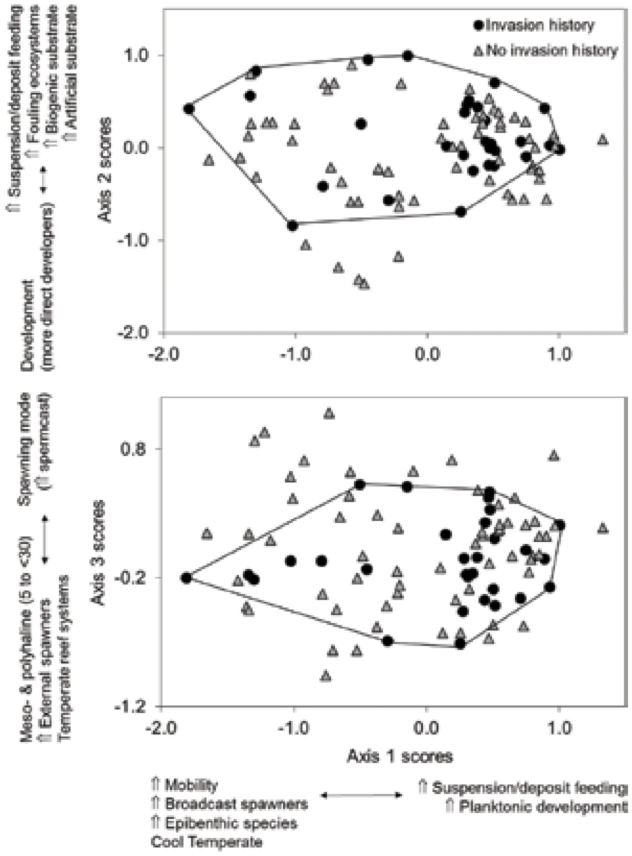

Figure 12-5. Ordination of 92 JTMD species based on life history and ecological traits. Axis 1 and Axis 2 scores (top graph) and Axis 1 and Axis 3 scores (bottom graph) for species with known invasion history (black filled circles) and no invasion history (grey filled triangles) are presented. Traits significantly correlated with axis scores are included along each axis. Polygons encompassing species with invasion history are presented for reference. See Table 12-1 for additional details on the correlation analysis.

Quantitative analysis

Geographic distribution and invasion history

The variability in geographic distribution among the 92 species with and without known invasion history, which excludes the five cryptogenic species and six species with insufficient data for quantitative analysis, was well-described with a three-dimensional NMS ordination that accounted for 86% of the variation in species' geographic distributions (stress = 8.9, 51 iterations) (Figure 12-4). Axis 1 accounted for 44% of the variation, Axis 2 for 29% of the variation, and Axis 3 for 13% of the variation. Along Axis 1, species distributed within the Central Indo-Pacific ($r = -0.547$, adjusted $P < 0.001$) were separated from those within the Temperate North Pacific ($r = 0.928$, adjusted $P < 0.001$). Along Axis 2, species from the Central Indo-Pacific ($r = -0.625$, adjusted $P < 0.001$) and the Western Indo-Pacific ($r = -0.499$, adjusted $P < 0.001$) were separated from species within the Temperate North Atlantic

(r = 0.723, adjusted $P < 0.001$). Axis 3 scores were positively correlated with the Central and Eastern Indo-Pacific (r = 0.528, adjusted $P < 0.001$). However, there were no differences in the geographic distribution of species with and without invasion history (MRPP; $A = 0.004$; $P = 0.36$).

Environmental and life history traits and invasion history

A three-dimensional ordination of the 92 species with and without known invasion history based on environmental and life history traits also accounted for a high level of variation (89.7%) within the data matrix (stress = 11.6, 103 iterations) (Figure 12-5). Axis 1 accounted for 62.0% of the variation and separated species based on mobility, spawning mode, trophic status, developmental mode, habitat, and temperature regime (Table 12-1). Axis 2 accounted for 18.9% of the variation in the dataset and separated species primarily on developmental mode, trophic status, ecosystem, and substrate. Axis 3 accounted for 8.9% of the total variation and separated species based on salinity tolerance and spawning and reproductive.

There was also a significant statistical separation between species with and without invasion histories based on environmental and life history traits (MRPP, $A = 0.03$, $P = 0.003$). Based on ISA, species with and without invasion history were differentiated by substrate, ecosystem, and salinity and temperature ranges (Table 12-2). Species with a known invasion history were reported on artificial

Table 12-1. Correlations between Axis 1, 2, and 3 scores from the Nonmetric Multidimensional Scaling (NMS) ordinations and the JTMD species traits. Ordination included 92 species.

Traits	Axis 1	Traits	Axis 2	Traits	Axis 3
Trophic status*	0.873	Trophic status*	0.424	Spawning mode (broadcast ⇒ spermcast)	0.606
Development (direct ⇒ planktonic)	0.482	Fouling ecosystems	0.395	Cool temperate	–0.391
Euhaline (30 to <40 ppt)	–0.374	Biogenic substrate	0.382	Artificial substrate	–0.395
Infaunal habitats	–0.438	Artificial substrate	0.358	Reproductive mode (internal ⇒ external spawners)	–0.478
Tidal flat ecosystems	–0.460	Development (direct ⇒ planktonic)	–0.802	Temperate reef ecosystems	–0.539
Cool temperate	–0.459			Meso- and polyhaline (5 to <30 ppt)	–0.554
Epibenthic	–0.513				
Spawning mode (broadcast ⇒ spermcast)	–0.628				
Mobility (less ⇒ more mobile)	–0.889				

*More positive values of trophic status indicate more suspension and deposit feeding.
Only correlations that were significant after correction for multiple tests are included ($P < 0.0008$; $|r| > 0.355$). "⇒" indicates the trait gradient from negative to positive axis scores. For example, the positive correlation between Axis 1 scores and the trait "Spawning mode" indicates that species with more positive Axis 1 scores displayed more spermcasting than species with less positive or negative scores. A negative correlation with a habitat trait, such as "Epibenthic", means that species occurring in epibenthic habitats were significantly associated with negative Axis 1 scores. See Appendix 12-2 for additional information on trait details.

Table 12-2. Traits and associated Indicator Values and P-values that were identified in Indicator Analysis for species with and without know invasion history.

Trait[1]	Indicator Value (IV)	Randomized Indicator Value (IV)	P-value
Artificial substrate	64.90	36.50	<0.001
Hardpan substrate	23.30	6.80	<0.001
Temperate reef ecosystems	53.20	31.30	<0.001
Fouling ecosystems	54.30	35.90	0.001
Polyhaline survival salinities (18 to <30 ppt)	52.40	40.60	0.008
Tropical survival temperatures	41.20	23.80	0.003
Mesohaline survival salinities (30 to <40 ppt)	37.50	23.80	0.010
Hypersaline survival salinities (>30 ppt)	17.20	7.50	0.014
Subtropical survival temperatures	45.40	32.00	0.014
Flotsam ecosystems	22.70	12.00	0.019

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[1] All of the traits were positively associated with species with known invasion history, i.e., association with artificial substrate and occurrence in fouling ecosystems were more common in species with known invasion history.

Table 12-3. List of the 35 JTMD species with no known invasion history that overlapped in three-dimensional trait space with species with known invasion history.

Phylum/Subphylum	Genus and species
Echinodermata	*Aphelasterias japonica*†[β]
Crustacea	*Balanus crenatus*[β]
Bryozoa	*Callopora craticula*[β]
Bryozoa	***Celleporina porosissima***†[β]
Mollusca	*Dendronotus frondosus*[β]
Bryozoa	*Escharella hozawai*†[β]
Annelida	***Eulalia quadrioculata***[β]
Bryozoa	*Exochella tricuspis*†[β]
Crustacea	***Gammaropsis japonica***†[β]
Cnidaria	*Halecium tenellum*[β]
Annelida	*Halosydna brevisetosa*[β]
Crustacea	*Harpacticus septentrionalis*[β]
Mollusca	***Hermissenda crassicornis***[β]
Mollusca	*Hiatella orientalis*†[β]
Mollusca	*Hyotissa quercinus*[β]
Mollusca	*Laevichlamys cuneata*†[β]
Mollusca	***Laevichlamys squamosa***†[β]
Cnidaria	*Metridium dianthus* [β]
Bryozoa	*Microporella borealis*†[β]
Mollusca	*Mytilisepta virgata*†[β]
Mollusca	*Mytilus coruscus*†[β]
Mollusca	*Mytilus trossulus*[β]
Crustacea	***Oedignathus inermis***[β]
Crustacea	*Parastenhelia spinosa*[β]
Mollusca	***Pascahinnites coruscans***†
Crustacea	***Pseudoctomeris sulcata***†[β]
Crustacea	*Semibalanus cariosus*[β]
Cnidaria	*Sertularella mutsuensis*†[β]
Bryozoa	*Smittoidea spinigera*†[β]
Crustacea	***Sphaerozius nitidus***†
Annelida	*Syllis elongata*[β]
Mollusca	*Teredothyra smithi*†[β]
Bryozoa	*Tubulipora misakiensis*†[β]
Bryozoa	*Tubulipora pulchra*[β]
Bryozoa	*Watersipora mawatarii*†[β]

† indicates the 19 species not reported to occur in the Northeast Pacific Ocean.
[β] indicates the 33 species not reported to occur in the Eastern Indo-Pacific.
Species in bold lettering were collected from only one debris item.

and hardpan substrates ($P < 0.001$), in fouling habitats ($P = 0.001$), and associated with temperate reefs ($P < 0.001$) more often than species with no prior invasion history. Species with prior invasion history were also more commonly found in flotsam ecosystems ($P = 0.019$), exhibited greater salinity tolerance ($0.003 \leq P \leq 0.014$), and were more common at subtropical and tropical temperatures ($P < 0.015$) than species with no prior invasion history.

Finally, we identified 35 JTMD species with no known invasion history that overlapped in ordination space with those with known invasion history, including 3 Annelid species, 9 Bryozoans, 3 Cnidarians, 8 Crustaceans, 1 Echinoderm, and 11 Molluscs (Table 12-3). Of those, 9 species were collected from only one JTMD item (Table 12-3). Of the 35 species, there were 19 species not reported to occur within the Northeast Pacific region. Of those 19 species, 10 occur in cool, temperate waters. When considering warmer regions that received large amounts of JTMD, such as the Hawaiian Archipelago, there were 33 species not reported to occur in the Eastern Indo-Pacific Region, and 14 of those species occur in sub-tropical and 7 in tropical waters.

Discussion

Our objectives were to characterize variation in distributional, environmental, and life history traits within the unique assemblage of coastal species that comprise the JTMD species pool and determine which of those traits are distinct between JTMD species with and without known invasion histories. We identified traits associated with species that have prior invasion history, including a greater occurrence on artificial substrate and in fouling ecosystems and greater salinity tolerance. The 35 species that overlapped in the ordination with the 30 species that have a prior invasion history display a similar suite of traits, i.e., they were more common on artificial substrate (2.2 x), in fouling ecosystems (1.5 x), and in polyhaline waters (1.5 x) than those species that did not overlap. The ability to colonize artificial substrate and survive in fouling ecosystems has obvious implications for invasion potential. Additionally, our observation that JTMD species with a known invasion history exhibited greater salinity tolerance has been reported previously for both invertebrates and fishes (Kolar and Lodge, 2002; Devin and Beisel, 2007). Furthermore, Devin and Beisel (2007) presented their results as support for the hypothesis that invasive species can tolerate a wider range of environmental conditions and suggested that studies that combine biological and ecological characteristics, such as this study, could lead to better delineation of invader profiles.

Prior invasion history has been identified as a potential predictor of future invasion success (Williamson and Fitter, 1996; Ricciardi and Rasmussen, 1998; Kolar and Lodge, 2002). In fact, species watch lists are often comprised of species notorious in other parts of the world, although transporting large numbers of species outside of their native range can have unexpected and unpredictable consequences that transcend past histories (Carlton and Geller, 1993). The 30 JTMD species with a known invasion history clearly warrant further consideration. However, given that marine debris is a relatively new

L-R, not to scale: *Hemigrapsus sanguineas*, National Museum of Nature and Science, Tokyo; *Mytilus galloprovincialis*, Wikimedia Commons; *Jassa marmorata*, Adriana Radulovici; *Megabalanus rosa*, Jim Carlton; *Eutima japonica,* Leslie Harris.

and poorly documented transport vector for coastal organisms, we were interested in developing an approach to quantitatively evaluate the potential invasion risk for species with no invasion history that were transported on JTMD. Based on our approach, we excluded 27 of the original 62 species that did not overlap in ordination space with the JTMD species with known prior invasion history, leaving 35 remaining species that did overlap with JTMD species with prior invasion histories. For the Northeast Pacific, that list could be reduced to the 10 species that are not currently present but are reported to occur in cool, temperate waters as these species would be more likely to survive in the conditions of the Northeast Pacific. For the Eastern Indo-Pacific region, the list of 33 species not currently present could be reduced to 7 or 14, if limited to species reported to occur in tropical or sub-tropical waters, respectively. Those species could be further ranked or prioritized based on more detailed climate matching or consideration of regional habitat availability. Thus, a method of identifying species based on similarities in trait space could complement other risk assessment techniques based on, or strongly influenced by, prior invasion history (Kulhanek et al., 2011; Therriault et al., 2018).

Some of the 35 JTMD species with no known prior invasion history that overlap in trait space with species with known invasion histories have been documented to occur on other transport vectors. This is not surprising as many species are transported in ballast water or on ship hulls and have not become invasive (Nentwig, 2007), although it does provide additional information about the transport potential of JTMD species. The bryozoan *Exochella tricuspis* has been reported previously on marine debris (Kiessling et al., 2015). The copepod *Harpacticus septentrionalis* (Ólafsson et al., 2001) was reported drifting with algae. Two additional species, the barnacle *Semibalanus cariosus* and mussel *Mytilus trossulus*, have been reported as hull foulers (Zyagintsev, 2000). As the prevalence of marine debris, particularly long-lived plastics, increases (Derraik, 2002; Cózar et al., 2014), the transport of marine species associated with marine debris will likely grow (Aliani and Molcard, 2003; Carson et al., 2013), increasing the transport potential for many coastal species and providing additional opportunities for establishment outside of their current distributional ranges (Barnes, 2002; Wonham and Carlton, 2005; Gregory, 2009).

Collectively, JTMD species are distributed around the world, but the majority are native to the Northwest Pacific region. Within our 103 JTMD species, 2 of the 30 species with known invasion histories, *Mytilus galloprovincialis* and *Asterias amurensis*, are listed on the 100 worst invaders list[3]. Additionally, some species have native distributions throughout the North Pacific, such as *Oedignathus inermis*, suggesting natural, widespread dispersal. However, it is possible, perhaps even likely, that the individuals or groups of individuals from the Northwest Pacific arriving on JTMD in the Northeast and Eastern Indo-Pacific are genetically distinct from those already present where they land, as has been shown for algae associated with JTMD (Hanyuda et al., 2018). While beyond the scope of this effort, the genetic architecture of invading individuals can influence their establishment, dominance, and growth rate and is an important consideration (Tsusui et al., 2000; Sakai et al., 2001).

Based solely on geographic distribution, there was no distinction between species with and without invasion history. However, when the environmental and life history traits were examined, species with an invasion history were differentiated from those without invasion history. Our database was limited due to lack of pertinent life history information across all species, such as longevity, reproductive effort, and growth rate. This was due, in part, to the fact that some JTMD taxa are relatively poorly known in general (e.g., bryozoans), thus trait information was limited. Despite this limitation, certain traits, including habitat, ecosystem, and salinity and temperature tolerance, separated species with and without known invasive history. Thus, it is likely that with more detailed information on life histories and environmental requirements, greater separation between the species with and without known invasion history, and clearer delineation of an invader profile would be possible (Verberk et al., 2013).

JTMD species had to have broad coverage across traits for inclusion in our analysis. This was the only criterion as there was no systematic selection of species for analysis. However, a taxon had to be identified to species (or rarely a species complex, such as the *Jassa marmorata*-complex) with a high level of confidence for inclusion. Therefore, there could be some biased representation based on ease of identification, prior knowledge of taxa, and somewhat uneven taxonomic effort across phyla. There is also likely to be some size-dependent bias, where species with small body sizes have arguably the lowest likelihood of detection and identification (Ruiz et al., 2000). Overall, however, we consider the 103 species to be a representative subset of the macro-invertebrate biota that have been documented on JTMD.

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[3] http://www.iucngisd.org/gisd/100_worst.php

The Great East Japan earthquake and tsunami resulted in catastrophic loss and suffering. Despite the monumental challenges associated with recovery and rebuilding efforts, the Ministry of the Environment in Japan generously committed substantial resources to improve collective understanding of the JTMD debris field and associated biota and evaluate potential risks. The more than 630 JTMD items collected and examined since the tsunami likely represent a relatively small fraction of the total debris field. However, their recovery and the subsequent identification of JTMD taxa improve our ability to understand and evaluate marine debris as a transport vector and JTMD species as potential invasive species.

The effort to collate and synthesize distributional, environmental, and life history information on JTMD species contributes to the depth and breadth of our understanding of species transported on this novel ocean vector. We characterized trait variation in many of the coastal species transported on JTMD and identified traits that differentiated JTMD species with and without known invasion history. Collectively, this study presents a quantitative trait analysis for prioritization of species with no invasion history and also provides a working hypothesis regarding traits that may increase the propensity for rafting coastal invertebrates to invade novel regions. Our efforts can complement other approaches to identifying species of concern (see Chapter 15).

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Chapter 12 Appendices

Appendix 12-1. List of the 103 Japanese Tsunami Marine Debris species included in distributional, environmental, and life history analysis

Appendix 12-2. Trait name and associated field values for all JTMD species included in the analysis

Appendix 12-1. List of the 103 Japanese Tsunami Marine Debris species included distributional, environmental, and life history analysis

Phylum	Species	Known invasion history	Cryptogenic
Annelida	*Amblyosyllis speciosa*		
Cnidaria	*Amphisbetia furcata*		
Crustacea	*Ampithoe lacertosa*		X[1]
Crustacea	*Ampithoe valida*	X	
Echinodermata	*Aphelasterias japonica*		
Echinodermata	*Asterias amurensis*	X	
Crustacea	*Balanus crenatus*		
Crustacea	*Balanus glandula*	X	
Crustacea	*Balanus trigonus*	X	
Mollusca	*Bankia carinata*		X
Mollusca	***Bankia bipennata***[2]		
Bryozoa	*Biflustra grandicella*	X	
Bryozoa	*Biflustra irregulata*	X	
Bryozoa	*Callopora craticula*		
Crustacea	*Caprella mutica*	X	
Bryozoa	*Celleporella hyalina*	X	
Bryozoa	*Celleporina porosissima*		
Crustacea	*Chthamalus challengeri*	X	
Foraminifera	***Cibicidoides lobatulus***		
Mollusca	*Crassostrea gigas*	X	
Mollusca	*Crepidula onyx*	X	
Bryozoa	*Cryptosula pallasiana*	X	
Crustacea	*Dactylopodamphiascopsis latifolius*		
Mollusca	*Dendostrea folium*	X	
Mollusca	*Dendronotus frondosus*		
Cnidaria	*Diadumene lineata*	X	
Chordata	*Didemnum vexillum*	X	
Mollusca	*Dolabella auricularia*		
Crustacea	*Dynoides spinipodus*		
Arthropoda	*Endeis nodosa*	X	
Bryozoa	*Escharella hozawai*		
Annelida	*Eulalia quadrioculata*		
Cnidaria	*Eutima japonica*		
Bryozoa	*Exochella tricuspis*		
Crustacea	*Gammaropsis japonica*		
Cercozoa	***Gromia oviformis***		
Arthropoda	*Halacarellus schefferi*		
Cnidaria	*Halecium tenellum*		
Annelida	*Halosydna brevisetosa*		
Crustacea	*Harpacticus nicaeensis*		
Crustacea	*Harpacticus septentrionalis*		
Echinodermata	***Havelockia versicolor***		
Crustacea	*Hemigrapsus sanguineus*	X	
Mollusca	*Hermissenda crassicornis*		
Crustacea	*Heterolaophonte discophora*		
Mollusca	*Hiatella orientalis*		
Cnidaria	***Hydrodendron gracile***		
Annelida	*Hydroides ezoensis*	X	
Mollusca	*Hyotissa quercinus*		
Crustacea	*Ianiropsis serricaudis*	X	
Crustacea	*Jassa marmorata*-complex	X	
Mollusca	*Laevichlamys cuneata*		
Mollusca	*Laevichlamys squamosa*		
Mollusca	*Limaria hirasei*		
Mollusca	*Lyrodus takanoshimensis*	X	
Crustacea	*Megabalanus rosa*	X	
Crustacea	*Megabalanus zebra*	X	
Cnidaria	*Metridium dianthus*		
Bryozoa	*Microporella borealis*		
Mollusca	*Mitrella moleculina*		
Mollusca	*Modiolus nipponicus*		
Mollusca	*Mopalia seta*		
Mollusca	*Modiolarca cuprea*		
Mollusca	*Mytilisepta virgata*		
Mollusca	*Mytilus coruscus*		
Mollusca	*Mytilus galloprovincialis*	X	

Appendix 12-1. List of the 103 Japanese Tsunami Marine Debris species included distributional, environmental, and life history analysis (cont'd)

Phylum	Species	Known invasion history	Cryptogenic
Mollusca	*Mytilus trossulus*		
Mollusca	*Nipponacmea habei*		
Cnidaria	*Obelia longissima*		X
Crustacea	*Oedignathus inermis*		
Nemertea	*Oerstedia dorsalis*		
Cnidaria	*Orthopyxis platycarpa*		
Crustacea	*Paralaophonte congenera*		
Crustacea	*Paramphiascella fulvofasciata*		X
Crustacea	*Parastenhelia spinosa*		
Crustacea	*Parathalestris intermedia*		
Mollusca	*Pascahinnites coruscans*		
Mollusca	*Patinopecten yessoensis*		X
Echinodermata	*Patiria pectinifera*		
Annelida	*Perinereis nigropunctata*		
Sipuncula	*Phascolosoma scolops*	X	
Mollusca	***Placiphorella stimpsoni***		
Cnidaria	*Pocillopora damicornis*		
Crustacea	*Pseudoctomeris sulcata*		

Phylum	Species	Known invasion history	Cryptogenic
Annelida	*Pygospio californica*		
Crustacea	*Sarsamphiascus minutus*		
Bryozoa	*Schizoporella japonica*	X	
Crustacea	*Semibalanus cariosus*		
Cnidaria	*Sertularella mutsuensis*		
Bryozoa	*Smittoidea spinigera*		
Crustacea	*Sphaerozius nitidus*		
Crustacea	*Stenothoe crenulata*-complex	X	
Annelida	*Syllis elongata*		
Arthropoda	*Telmatogeton japonicus*	X	
Echinodermata	*Temnotrema sculptum*		
Mollusca	*Teredo navalis*	X	
Mollusca	*Teredothyra smithi*		
Nemertea	*Tetrastemma nigrifrons*		
Bryozoa	*Tricellaria inopinata*	X	
Annelida	*Trypanosyllis zebra*		
Bryozoa	*Tubulipora misakiensis*		
Bryozoa	*Tubulipora pulchra*		
Bryozoa	*Watersipora mawatarii*		

[1] Species with a known invasion history or a cryptogenic origin are indicated by an "X". All other species have no known invasion history.

[2] Species in bold were included in the qualitative synthesis but not the quantitative analysis due to lack of information.

Appendix 12-2. Trait name and associated values for all JTMD species included in the analysis

Trait	Definition
Native realm	
Realm_1	Arctic
Realm_2	Temperate Northern Atlantic
Realm_3	Temperate Northern Pacific
Realm_4	Tropical Eastern Pacific
Realm_5	Tropical Atlantic
Realm_6	Eastern Indo-Pacific
Realm_7	Central Indo-Pacific
Realm_8	Western Indo-Pacific
Realm_9	Temperate South America
Realm_10	Temperate Southern Africa
Realm_11	Temperate Australasia
Realm_12	Southern Ocean
Native region	
Reg_1	Arctic
Reg_2	High Arctic
Reg_3	Northeast Atlantic
Reg_4	Northwest Atlantic
Reg_5	Mediterranean Sea
Reg_6	Ponto-Caspian
Reg_7	Northeast Pacific
Reg_8	Northwest Pacific
Reg_9	Tropical Eastern Pacific
Reg_10	Magellanic
Reg_11	Southeast Pacific
Reg_12	East Tropical Atlantic
Reg_13	West Tropical Atlantic
Reg_14	Southwest Atlantic
Reg_15	Southern Africa
Reg_16	Central Indo-Pacific
Reg_17	Eastern Indo-Pacific
Reg_18	Indian Ocean
Reg_19	Southern Australia and New Zealand
Reg_20	Antarctica
Native temperature regime	
Temp_1	Cold water
Temp_2	Cool temperate
Temp_3	Warm temperate
Temp_4	Subtropical
Temp_5	Tropical
Native salinity regime	
Sal_1	Freshwater = <0.5 ppt
Sal_2	Oligohaline = 0.5–<5 ppt
Sal_3	Mesohaline = 5–<18 ppt
Sal_4	Polyhaline = 18–<30 ppt
Sal_5	Euhaline = 30–<40 ppt
Sal_6	Hypersaline = ≥ 40 ppt

Trait	Definition
Fertilization mode	
1	Internal fertilization
2	External fertilization
Reproductive mode	
1	Gonochoristic/dioecious
2	Hermaphroditic/monoecious
Spawning type	
1	Broadcast
2	Spermcast
3	Not applicable
Development mode	
1	Direct development
2	Benthic larva
3	Lecithotrophic larva
4	Planktotrophic larva
5	Planktonic larva type unspecified
6	Lecithotrophic and planktotrophic (Dendronotus frondosus only)
Adult mobility	
1	Sessile
2	Facultatively mobile: species with limited mobility, in particular to repositioning themselves in response to environmental disturbances, e.g., sea anemones
3	Actively mobile: mobility is a normal part of at least part of the adult life cycle - at least in spurts. Not dependent upon distance traveled
Depth regime	
Depth_1	Supralittoral
Depth_2	Intertidal
Depth_3	Shallow subtidal = >0–30 m
Depth_4	Deep subtidal = >30–200 m
Depth_5	Bathyal = >200 m

Appendix 12-2. Trait name and associated values for all JTMD species included in the analysis (cont'd)

Trait	Definition
Ecosystem	
Eco_1	Coastal shore = Sediment environments along the coast that are affected by the tides and water activity shore waves, i.e., sandy beaches
Eco_2	Tide flats = Relatively flat, sediment areas that are submerged or exposed by the changing tides. Includes mud flats
Eco_3	Sediment subtidal = Sediment that is covered by a body of water at all times, without exposure to air due to tides
Eco_4	Submerged aquatic vegetation SAV= Sediment environments that include and are dominated by aquatic plants that are covered by water, i.e., seagrass
Eco_5	Marsh = Intertidal sediment environments dominated by vegetation that is rooted in the soil, i.e., marsh grasses and salt tolerant succulents
Eco_6	Rocky = Rocky intertidal rocky environments on coastal shore that are periodically exposed to both air and water. The zone between the high and low tide mark and rocky subtidal rocky environments below low tide mark that are always submerged by water
Eco_7	Coral reef = Areas where the rocky substrate is dominated by reef forming coral animals
Eco_8	Temperate reef = Oyster/mussel reef hard substrate that is covered or formed by bivalve shells; Worm Reef hard substrate that is predominantly composed of worm tubes; Coralline Algae Hard substrate that is predominantly composed of calcified algae, either the encrusting or unattached rhodolith form
Eco_9	Mangrove = Intertidal sediment environments dominated by salt-tolerant trees and shrubs. Found in tropical and subtropical areas
Eco_10	Macroalgal beds = Sediment environments where macroalgae are dominant and shape the habitat characteristics, e.g., algal mats of Ulva, Porphyra
Eco_11	Kelp forest = Hard substrate that supports the growth of very large brown algae Laminariales and/or Fucales. These habitats tend to be subtidal and occur in mid and high latitudes
Eco_12	Fouling = Hard substrate such as a boat hull that supports a community of organisms
Eco_13	Water column = Open water habitat where organisms are completely surrounded by water no surfaces, sides, or floors; within the pelagic zone
Eco_14	Floating plants or macroalgae = Large mats/rafts of plants or algae that float unattached on the water's surface in the open ocean
Eco_15	Flotsam = Aggregated floating debris in the open ocean

Trait	Definition
Habitat	
Hab_1	Pelagic = Organisms inhabiting the water column exclusive of the layer immediately above the bottom
Hab_2	Demersal = Mobile animals living on or near the bottom and that swim as a normal part of their routine and not just in response to disturbance
Hab_3	Epibenthic = Sessile e.g., barnacles, algae and vagile, e.g., snails organisms living on the surface of inorganic hard substrates including man-made structures, Epiphytic = Living on surface of living or dead plant, or Epizoic = living on surface of a living or dead animal
Hab_4	Under rock = Species that live beneath rock or other hard substrates e.g., shell rubble, debris
Hab_5	Borer = Organisms that bore into living or dead hard substrate
Hab_6	Infaunal = Animals living within sediment; Semi-infaunal = Animals partially buried in sediment and partially exposed in the water column
Substrate	
Subst_1	Mud = ≥75% by weight of particles <0.063 mm in size
Subst_2	Sand = ≥75% by weight of particles in the size range of 0.063 - 2 mm
Subst_3	Mixed fine sediment = Combination of mud and sand, where the two classes constitute >95% of the weight
Subst_4	Rock: Gravel ≥75% by weight of particles in the range of 2 - 64 mm; Cobble ≥75% by weight of particles in the size range of 64–256 mm; Rock Boulder particles >256 mm or bedrock unbroken rock
Subst_5	Mixed sediments = Sand and mud with gravel or cobble, where gravel and cobble each constitute >5% but <75% of the sediment weight.
Subst_6	Organic sediment = Sediment with high proportion of vegetative detritus. >30% organic matter > 17% organic carbon
Subst_7	Hardpan = Sand, silt, or clay particles that are slightly cemented to well cemented together to form a hard, and often flat, consolidated surface
Subst_8	Biogenic = Substrate composed of the surface of living or dead organisms
Subst_9	Artificial substrate = Hard substrates placed into estuarine or oceanic environments
Trophic status	
1	Herbivore
2	Omnivore
3	Predator
4	Detritivore
5	Suspension feeder
6	Deposit feeder
7	Herbivore and suspension feeder
8	Suspension feeder and deposit feeder

John Chapman

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Chapter 13: Detection of invertebrates from Japanese Tsunami Marine Debris in North American waters

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Abstract

The Great Japan Tsunami of 2011 resulted in an unprecedented dispersal event of marine biota from Asian coastal waters to the Pacific shores of North America. While significant effort has focused on characterizing the spatial and temporal patterns of biota arriving to North America, the fate of these organisms and the extent of new invasions are poorly resolved. We report here new surveys to evaluate the presence of non-native marine species in Pacific North America, from California to Alaska, including free-living marine invertebrates and parasites reported on Japanese Tsunami Marine Debris (JTMD). These data provide important baseline measures (benchmarks) for the species pool present in North America before and during the JTMD dispersal event. We explore the inferences that can be drawn from this baseline and its application to evaluate invasions associated with JTMD, while also considering the potential for both lag-times in detection and other mechanisms (vectors) of introduction of biota from the northwestern Pacific.

We used mussels (*Mytilus* spp.) as a model system to explore the opportunity (risk) of parasite transfers. Mussels, one of the most frequent organisms on JTMD arriving to North America, are known to have a large number of parasitic and commensal species worldwide and in Japan, and some can cause severe disease and mortality. We tested over 1,000 mussels arriving on JTMD and detected at least three distinct parasite taxa. These results demonstrate that parasites (including commensals) arrived with invertebrate hosts on JTMD, increasing the total number of JTMD-associated taxa. In the case of mussels, detected parasites increased total diversity 4-fold, underscoring the potential for high levels of hidden parasite diversity among the nearly 380 invertebrate taxa detected on JTMD to date, since almost none of these have been tested for parasite species richness.

Our extensive surveys of mussels and fouling communities along the Pacific coast of North America, combined with comprehensive analysis of existing literature, detected no new invasions attributed clearly to JTMD-mediated transport. However, these analyses also reveal large numbers of species that have colonized North America from Japan by other vectors, prior to JTMD arrival. These results indicate that many invertebrate species in Japan, including some arriving on JTMD, are able to colonize North America, suggesting a high level of environmental match.

While our field-based surveys and synthesis of existing historical records have not detected JTMD-mediated invasions to date, it is still premature to draw any conclusions. The arrival of hundreds of distinct taxa and a high environmental match between Japan and Pacific North America provide significant opportunity for invasions. Despite extensive analysis to date, the likelihood of detecting invasions during our study is low because there are often significant lag times in detecting new invasions due to restricted geographic range, small population size, and limited sampling effort. Thus, full evaluation of resulting invasions requires repeated measures over time for selected sentinel sites, and would ideally (a) deploy molecular genetic techniques with high sensitivity and efficacy and (b) use the extensive baseline measures of historical occurrences established in our project.

Introduction

The overall purpose of the ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project was to characterize the arrival of marine biota to North America and Hawaii by JTMD and to evaluate the potential for new invasions to result from this transfer mechanism. The research aimed to: (1) detect new JTMD-associated invertebrate invasions to Pacific North American waters, (2) design and implement fouling panel surveys to detect new invertebrate invasions in Hawaii, and (3) evaluate resident populations of mussels in North America for the presence of known JTMD parasites and pathogens.

Methods

Surveys of invertebrate communities

We implemented standardized surveys of biofouling communities for bays in California, Oregon, Washington, British Columbia, and Alaska. Fouling panels were deployed in each state and in British Columbia, and a subset of these was collected for analyses to detect free-living JTMD invertebrate species in resident coastal waters of Pacific North America (Table 13-1). Between 2014 and 2016, we deployed fouling panels in eight different bays. Panels consisted of bare, dark gray, lightly sanded polyvinyl chloride (PVC) plates measuring 14 x 14 cm, attached to bricks with the collecting surface facing downward. Panels were suspended one meter below mean lower low water at randomly chosen locations on docks (Blum et al., 2007) for approximately three months, during the summer, to coincide with the period of high seasonal recruitment and provide sufficient time to develop mature communities (Ruiz et al., unpublished data).

We collected and processed panels at each of these locations, except those in Washington State (see below). The retrieval and processing in Prince Rupert was a joint effort with our Canadian PICES collaborators, along with the port of Prince Rupert and the local community college. For processing, panels were examined individually under dissecting microscopes, and invertebrates were identified initially in the field to morphospecies or lowest taxonomic level possible. Voucher specimens were collected for (a) further morphological analyses and identification and (b) genetic barcoding for independent verification and comparison with material collected by our Japanese colleagues. All morphological analyses were done by the Smithsonian Environmental Research Center (SERC). All vouchers for molecular genetic analyses were sent to Moss Landing Marine Labs (MLML).

Our highest priority locations for these surveys were Yaquina Bay, Oregon and Prince Rupert, British Columbia. These represented major gaps in our knowledge of non-native biota along the Pacific coast, having only limited surveys to date for biofouling species. Critically, Prince Rupert is a major port system but has only received limited attention to date (Gartner et al., 2016). As a major port, establishing a baseline of pre-existing invasions in Prince Rupert (i.e., those that pre-date JTMD arrivals) was deemed a high priority, since all other commercial ports in Pacific North America have been surveyed in the past decade. In the case of Yaquina Bay, this was a hotspot for JTMD species landings, such that measures here served both as baseline and detection effort. The dispersion of sample sites for these two locations is shown in Figure 13-1.

The sites from Washington were intended initially for collection in fall 2015, but strong rains and flooding occurred during the scheduled retrieval. Our intention was to retrieve these in 2016 (15 months after initial deployment), but we had significant losses during this time. Thus, samples from these bays are not available. However, each of these locations had a very small number of intended sites (unlike Yaquina Bay or Prince Rupert, with 10 sites each), and had a low impact to the overall study results. In addition to the surveys conducted during

Table 13-1. Locations of biofouling community surveys using standardized fouling panels.

State/Province	Location	# sites	# panels
California	**San Francisco Bay**	10	100
California	**Humboldt Bay**	10	50
Oregon	**Yaquina Bay**	10	50
Washington	Willapa Bay	2	20
Washington	Grays Harbor	2	20
Washington	Neah Bay	2	10
British Columbia	**Prince Rupert**	10	50
Alaska	**Ketchikan**	3	135

Bold indicates core sites with extensive surveys.

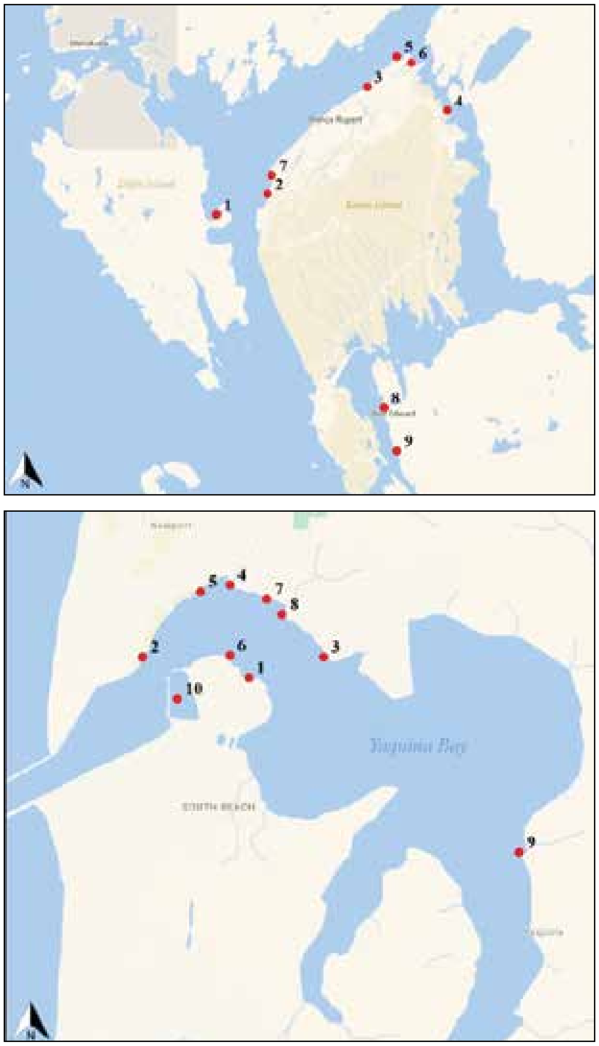

Figure 13-1. Sites of fouling panel surveys in (top) Prince Rupert, British Columbia and (bottom) Yaquina Bay, Oregon. Five fouling panels were analyzed from each site.

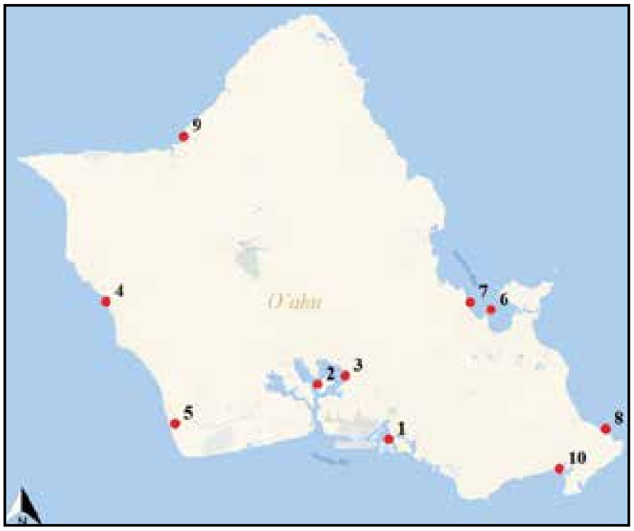

Figure 13-2. Sites of fouling panel surveys on Oahu, Hawaii. Five fouling panels were analyzed from each site.

the ADRIFT project, we have carried out identical surveys in several other bays in California waters in the past five years, giving further baseline data on resident species, prior to the JTMD landings.

We worked with colleagues in Hawaii to implement an identical biofouling survey to those along the Pacific coast of North America (above), and provided protocols to advance this work. In 2015, we focused on Oahu, with panels surveyed at 10 sites (50 panels total; Figure 13-2). These were retrieved and processed by SERC staff from December 6 to 18, 2015. This survey generated a similar set of vouchers for morphological and genetic analyses to those in North America.

In British Columbia, panels were deployed using similar methods at multiple sites in 2015, including those described previously for Prince Rupert. Panels were surveyed at 10 sites in Prince Rupert (50 panels total), five sites in Tofino (20), four sites in Ucluelet (30), and five sites in Haida Gwaii (40) (Figure 13-3). The Prince Rupert panels were retrieved from September 29 to October 8, 2015, the Haida Gwaii panels were retrieved from October 3 to November 3, 2015, and the Tofino and Ucluelet panels were retrieved from November 16 to 18, 2015. Only those panels from Prince Rupert were analyzed fully (see above). For the remaining locations, we developed joint protocols for standard photographs and a rapid assessment for target invertebrate species, and these panels were preserved for further potential analyses.

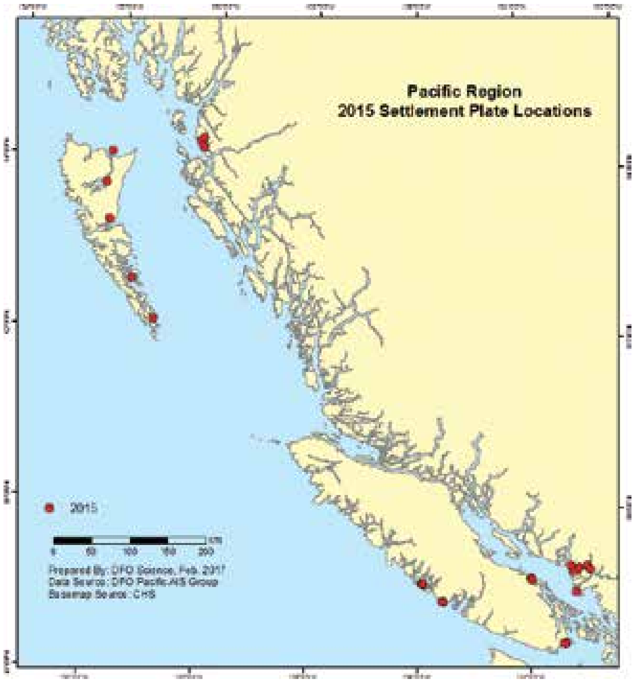

Figure 13-3. Sites of fouling panel surveys in British Columbia, Canada.

Surveys for parasites

The parasitic hydroid, *Eutima* sp. and species of haplosporidians were detected in mussels associated with JTMD arriving in Washington and Oregon (Calder et al., 2014; see Chapter 7). To survey for these same parasites in resident populations of mussels in Pacific North America, mussels were collected and processed from bays in California to Alaska. We obtained mussels (50–150 per bay) through direct collections and assistance from colleagues at multiple sites. We obtained 4,087 mussels for multiple analyses (Table 13-2). The mussels were processed live in order to (a) visually survey for macroparasites, (b) preserve target tissues samples to screen genetically for protistan parasites (especially haplosporidians), and (c) preserve tissue to screen genetically for non-native mussel species. The screening for parasites focused on those taxa detected in mussels on JTMD, including the endoparasitic hydroid *Eutima* and other macroparasites, following the same protocols as described in Chapter 7. The mussel tissues were sent to MLML to be screened for Japanese mussel species.

Table 13-2. Mussels collected for analyses of parasites and host genetics of resident populations in Pacific North America.

Collection year	State / Province	Name	Total # *Mytilus* collected	Total # DNA samples collected for host ID	Total # DNA samples collected for protistan parasite ID	Total # *Mytilus* samples screened for macroparasites
2014	OR	Yaquina Bay	247	247	134	133
2014	OR	Coos Bay	277	277	144	144
2014	CA	Humboldt Bay	252	252	168	144
2014	CA	Bodega Bay	143	143	135	135
2014	CA	Tomales Bay	119	119	107	92
2014	CA	San Francisco Bay**	202	202	202	101
2015	AK	Sitka Sound	100	100	100	100
2015	CA	Newport Bay	100	100	99	100
2015	WA	Neah Bay	50	50	50	50
2015	AK	Ketchikan	342	339	238	329
2015	AK	Kachemak Bay	50	50	50	50
2015	BC	Prince Rupert	100	100	100	100
2015	AK	Seward	150	149	149	149
2015	OR	Coast south of Yaquina Bay	50	50	50	50
2015	AK	Prince William Sound, Orca Inlet	248	248	248	248
2015	CA	San Diego Bay	150	0	150	150
2015	BC	Nanaimo	60	60	60	60
2015	CA	Mission Bay	150	0	150	150
2015	CA	Long Beach	125	125	100	100
2015	CA	Oxnard	73	73	50	50
2015	CA	Santa Barbara	84	84	50	50
2015	BC	Saanich Inlet	50	50	50	50
2015	AK	Haines	47	46	44	47
2015	CA	Morro Bay	165	164	152	152
2015	CA	Elkhorn Slough	101	101	100	100
2015	CA	Monterey Bay	100	100	100	100
2015	CA	San Francisco Bay**	202	200	199	200
2016	BC	Vancouver	50	46	50	50
2016	WA	Grays Harbor	150	0	0	150
2016	WA	Willapa Bay	150	0	0	149
Total (all years, regions, and bays)			**4,087**	**3,475**	**3,229**	**3,483**

** Sampled twice
OR = Oregon, CA = California, WA = Washington, AK = Alaska, BC = British Columbia

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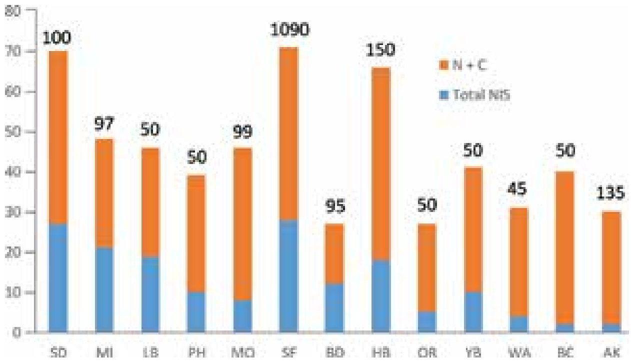

Figure 13-4 Total number of sessile invertebrate species detected per bay survey. The figure indicates the contribution of NIS versus all other taxa (N = Native, C = Cryptogenic). Number of panels surveyed per bay shown on top of bars, and bay shown on x-axis includes (left to right): San Diego, California (SD); Mission Bay, California (MI), Long Beach, California (LB), Port Hueneme, California (PH), Morro Bay, California (MO); San Francisco Bay, California (SF); Bodega Bay, California (BD); Humboldt Bay, California (HB); Coos Bay, Oregon (OR); Yaquina Bay, Oregon (YB); Puget Sound, Washington (WA); Prince Rupert, British Columbia (BC); Ketchikan, Alaska (AK).

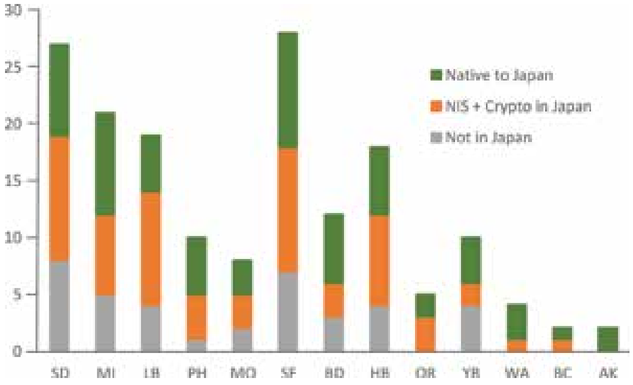

Figure 13-5. Total number of non-indigenous sessile invertebrates detected per bay survey. The figure indicates the number of species per bay that are considered (a) native to Japan, (b) occur in Japan as introduced (NIS) or cryptogenic, or (c) are not reported to occur in Japan. Bay identification for each bar and sample size per bay as shown in Figure 13-4.

Results

Surveys for invertebrate communities

Our surveys of the biofouling communities for Pacific North America detected no new records of potential JTMD species for sessile marine invertebrates based on morphological identification of specimens. While our study focused primarily on five selected bays (Table 13-1), we also conducted contemporary surveys in additional eight bays along this same coast, allowing for a much broader analysis of non-indigenous species (NIS) for Pacific North America. Across the 13 bays, 27 to 71 sessile invertebrate species per bay were detected, including 8 to 27 NIS per bay (Figure 13-4). NIS represented from 5 to 44% of all detected species per bay, with the lowest prevalence found at northern sites, including Alaska, British Columbia, and Washington sites (7, 5, and 12% NIS, respectively).

Of particular relevance for the ADRIFT project is the extent of shared biota with Japan, when considering only the NIS detected in each bay survey (Fofonoff et al., 2003). Figure 13-5 shows the total number of non-indigenous sessile invertebrates detected in each bay survey, according to their status in Japan. The figure identifies the number of species that are not known in Japan versus those that are known to occur there, distinguishing further those that are considered native to Japan and those that are either introduced or cryptogenic there. The majority of NIS detected in our surveys are reported to occur in Japan, ranging from 70–100% of NIS detected per bay (Figure 13-5). A much smaller percentage of these (<50% – excluding Alaska, British Columbia, and Washington sites, where the total number of NIS is low) are considered native to Japan.

Importantly, our survey results served a dual purpose. First, we did not detect new invasions to Pacific North America that were associated with JTMD. Second, we have established a strong baseline of field-based measures that (a) account for previously known invasions and (b) improve our capacity to detect potential JTMD invasions in the future (see Discussion).

Surveys of resident mussel populations

Of the 3,483 mussels screened for *Eutima* sp. from resident North American populations from California to Alaska during the ADRIFT project, none tested positive (Figure 13-6). However, 11 sites tested positive for the parasitic *Mytilicola orientalis*, including a new record for Alaska. This parasite, native to Japan, was already known to occur along the Pacific coast of North America, and was likely introduced with the oyster *Crassostrea gigas* in the early 1900s (Fofonoff et al., 2003).

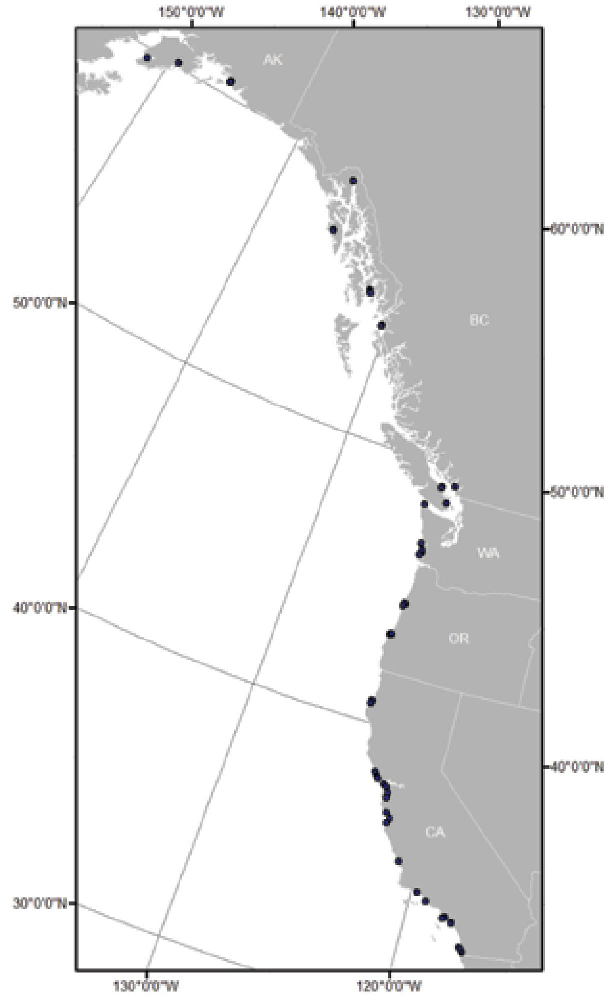

Figure 13-6. Mussel survey locations. Solid circles indicate location of sites sampled (*n* > 50 mussels). No *Eutima* sp. were detected in any mussels screened from any location.

Discussion

These results add several dimensions to our understanding of the dynamics of biota transferred by JTMD and the associated potential for new invasions in North America. First, we tested for the known extent of invasions on the Pacific coast of North America using field-based surveys and literature-based synthesis to detect new invasions. Second, we highlighted the potential role of parasite taxa in biotic transfers with JTMD. Third, we have also begun to explore the strong environmental match between Japan and Pacific North America, evaluating further the potential for colonization. We address each of these topics below.

Extent of previous invasions to North America from Japan

Our summary of extensive field-based surveys and a comprehensive synthesis of existing historical records provided several important insights about (a) past invasions from Japan and (b) the potential for invasions associated with JTMD arriving to North America. Our analyses quantify the extent to which past invasions from Japan have occurred, due especially to live importation of oysters (and associated biota) in the 20th century (Carlton, 1979; Cohen and Carlton, 1995; Ruiz et al., 2011), prior to any species transport by JTMD. Critically, this synthesis of data allows us to remove the confounding effect of historical invasions, to evaluate whether new species of putative JTMD origin have been detected to date.

We have no evidence to date of new invasions on the Pacific coast of North America that can be attributed to JTMD, based on the morphological analyses conducted (see Chapter 8 for molecular genetic analyses). We have also established a solid quantitative baseline and historical record of the invertebrate species present throughout Pacific North America. This baseline will allow the evaluation of any future invasions and the assessment of whether JTMD was a plausible mechanism for any future introductions.

However, it is unlikely that we would detect new invasions within a few years of arrival, unless they underwent a population explosion and spread rapidly in an area we sampled. Thus, it is premature to draw any conclusions about actual invasions, especially without further and repeated measures over time. Ideally, this would include molecular genetic methods, which promise high sensitivity and efficacy, drawing on the DNA barcode library developed during this project (see Chapter 8). Moreover, one could use initial zooplankton community samples already collected from several areas to advance this analytical approach.

Parasite invasions

For the hydroid parasite, *Eutima* sp., we conducted extensive surveys across many sites in North America, from Alaska to southern California, failing to detect any individuals. This demonstrates that the species is certainly not a common resident and unlikely to have colonized historically due to another vector. We surmise that the parasite would be widespread if introduced historically, given its high prevalence in Japan (Baba et al., 2007) and also the fact that the same mussel host is abundant in some parts of North America.

While we have confidence in the historical absence of *Eutima* sp., it is more challenging to assess whether a recent invasion may have resulted from JTMD-mediated transfers. Specifically, the probability that we would detect a nascent population (just beginning to develop) is low because it would likely be very restricted geographically to a small area and low in prevalence. This challenge is well-recognized in invasion ecology, and can result in significant lag times between initial colonization and detection (Crooks and Soule, 1999; Ruiz et al., 2000; Solow and Costello, 2004; Crooks, 2005). Thus, it is premature to assess whether an invasion of *Eutima* has occurred because detection may lag years to decades from any colonization event(s) and will be greatly dependent upon search effort, sensitivity of methods, and dynamics of any such population.

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For haplosporidians detected on JTMD, the situation is more complicated. In addition to the challenges outlined for *Eutima* sp., it is not clear whether these particular haplosporidians were already present in Pacific North America. While we have collected tissue samples for such an assessment, resources were not available for analysis during the project. Thus, further efforts are required to resolve both the taxonomic identity and biogeography for these parasites.

Environmental match between Japan and Pacific North America

Another important outcome from our analysis is the large number of NIS in Pacific North America that also occur in Japan, whether native or not in the latter region (Figures 13-3 and 13-4). This underscores the high potential environmental match between these two regions, demonstrating that many species have the capacity (indeed the history) of successfully colonizing both regions. Moreover, several of the species detected on JTMD were previously introduced by other vectors and have successfully established along the Pacific coast of North America, indicating further that the JTMD vector is delivering species capable of colonization. While this species overlap provides a coarse measure of potential "match", a next step in analysis is to use environmental niche models to formally assess the potential climatic range for several of these species. This may further refine predictions and be useful in identifying locations and taxa for future detection measures to assess whether JTMD invasions have occurred.

Acknowledgements

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OSU/Oregon Sea Grant/ODFW

Chapter 14: Detection of algae from Japanese Tsunami Marine Debris in North American waters

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Abstract

In order to evaluate the long-term invasion threat of Japanese Tsunami Marine Debris (JTMD) macroalgal species, we have undertaken field surveys to detect new algal invasions through visual searches for high profile JTMD species in anticipated habitats, and genetic screening for Japanese genetic types that could function as indicators of JTMD macroalgal species recruitment. We have been particularly vigilant for six JTMD algal species that are on the Global and/or Mediterranean Worst Invasive Alien Species Lists (*Undaria pinnatifida, Codium fragile* subsp. *fragile, Grateloupia turuturu, Antithamnion nipponicum, Polysiphonia morrowii*, and *Desmarestia viridis*). We surveyed natural habitat and artificial structures, including floating piers, in Alaska, British Columbia, Washington, and Oregon, and selected several localities as recommended long-term monitoring sites for detecting new invasions of JTMD macroalgae. Although our surveys continue, we have, to date, found only one possible macroalgal population in Pacific North America that may have been transported in JTMD.

Introduction

After being carried by currents across the North Pacific from Japan, marine debris items from the Great Japan Tsunami of 2011 have arrived on the Pacific coast of North America (Alaska, British Columbia, Washington, and Oregon) and Hawaii, bearing Japanese marine algae and benthic animals. The macroalgal species are often healthy and reproductive, and may recruit along these shores.

In order to evaluate the invasion threat of these algal species, we attempted to: (1) detect new algal invasions through visual searches for high profile Japanese Tsunami Marine Debris (JTMD) species in anticipated habitats, and genetic screening for Japanese genetic types that could function as indicators of JTMD macroalgal species recruitment, and (2) establish long-term monitoring sites for detecting possible future introduction of JTMD macroalgal species.

The research objective was to detect new algal invasions by surveying selected localities in Alaska, British Columbia, Washington, and Oregon. At these localities, we collected target specimens (the taxa identified as JTMD macroalgae) for genetic comparisons with Japanese and North American local populations of these species. We also aimed to select suitable localities for detecting new introduction of JTMD macroalgae.

Methods

In order to detect newly introduced macroalgal species on Pacific North American coasts and collect baseline data, we conducted field surveys (observations and collections) at selected localities in Alaska, British Columbia, Washington, and Oregon. Sampling focused on man-made structures as well as representative natural habitats. We concentrated on floating artificial structures, such as floating docks, because it is known that they are preferred habitats for both intertidal and subtidal macroalgae, and new introductions of non-indigenous species are often first noticed on such habitats.

The sampling team traveled to sites in Alaska, British Columbia, Washington State, and Oregon in 2015 and 2016 (Table 14-1) to survey the local area for species of seaweeds that may have arrived in those areas with JTMD (see Chapters 9 and 10). Three marinas and two natural beaches were sampled in each area of Alaska except for Sitka where only one natural beach was sampled (near an area on Kruzof Island where significant JTMD had been collected). Intermittent sampling has been conducted in the Sitka area in recent years (2006, 2010, 2011, 2013, 2014, and 2015), and the team did not feel it was necessary to sample local beaches again. The seaweeds of Ketchikan had not been sampled since 2000, and Kodiak had not been sampled since 2005. In September 2016, Bamfield, Tofino, and Ucluelet on the west coast of Vancouver Island, British Columbia, were surveyed. Three docks and three natural beaches were sampled in the Bamfield area, three docks in the Tofino area (natural beaches had been sampled there in May 2007), and three docks and one natural beach in Ucluelet (which was also sampled in May 2007). In Washington and Oregon, six floating docks, two jetties, and one bay were each surveyed two to three times to search for the new recruitment of JTMD species.

Visual searches were carried out for the larger JTMD algal species, and both large and small species were collected for later anatomical study and sequencing. Preliminary identifications were made based on morphological and anatomical examination of the specimens collected. Selected specimens were sequenced to confirm or expand these preliminary identifications.


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Hideaki Maki

Results

Of the 80 algal species found on JTMD during this study, 61% (49) had already been reported to occur in Pacific North America before the tsunami, and only 39% (31) were not yet present. We did not find new introductions of JTMD macroalgal species during the survey either in natural habitat or on artificial structures, including floating piers. All were known established populations prior to the tsunami event and were either native to the region or previously introduced by other vectors.

Washington State and Oregon

A number of the macroalgae species associated with JTMD (conspecifics) were identified during the current and also earlier surveys of natural and artificial habitats (Table 14-1; see also Appendix 9-5). All were found to be previously known from the area prior to the tsunami. Willapa Bay, Washington, had the highest number of JTMD-associated species present, followed by Grays Harbor, Washington.

Table 14-1. Algae survey locations and the observed total species richness of JTMD-associated species.

Field survey locations		**JTMD-associated species richness**
Alaska	Kodiak	5
	Sitka	6
	Ketchikan	6
British Columbia	Tofino	3
	Ucluelet	4
	Bamfield	5
	Prince Rupert	7
Washington	Olympic National Park	13
	Grays Harbor	18
	Willapa Bay	26
Oregon	Netarts Bay	9
	Boiler Bay	15
	Yaquina Bay	16
	Coos Bay	14
	Cape Blanco	2

British Columbia

The results of surveys in British Columbia are based on morphological and anatomical examination of the specimens collected (Table 14-1 and Appendix 14-1). Selected specimens were sequenced to confirm or expand these preliminary identifications. Of these species, only *Blidingia minima, Bryopsis* sp., *Cladophora* cf. *sericea, Ulva* cf. *intestinalis, Ulva* cf. *prolifera, Ulva lactuca*, and *Hincksia* cf. *granulosa* vs. cf. *sandriana* were also reported on JTMD. *Ulva linza* and *Analipus japonicus*, all listed on JTMD, were seen on natural beaches but not on docks. All of these species have long been recognized as part of the seaweed flora of Pacific North America (Scagel et al., 1989).

Ongoing annual sampling at Calvert Island, central coast of British Columbia, revealed the occurrence of a JTMD species in 2015. A Japanese species of *Pyropia* that was heretofore unknown in British Columbia was discovered there (Lindstrom, 2018). This species was collected from JTMD items that arrived in Washington and Oregon. In early June 2016, the site on northwest Calvert Island was revisited. Despite an intensive effort to locate the species at the same site it was collected at in 2015, only conchocelis of the species was detected. However, the gametophyte phase was again confirmed in 2017 and 2019. The timing of discovery of this species is coincidental with the tsunami event and while it cannot be confirmed as a JTMD introduction, monitoring for this species will continue.

Figure 14-1. Piers in Sitka, Alaska, and macroalgal vegetation on the floating dock (recommended long-term monitoring site).

Figure 14-2. Piers at Westport, Grays Harbor, Washington, and macroalgal vegetation on the floating docks (recommended long-term monitoring site).

Alaska

Of the algal species observed in Alaska, only *Cladophora sericea, Ulva* spp., *Hincksia sandriana*, and *Saccharina* spp. (*S. japonica/angustata*, close relatives of *S. latissima*) were reported on JTMD. Other species found on Alaska docks that were also found on JTMD, but not recorded from Prince Rupert, included *Blidingia minima* (Kodiak), *Desmarestia viridis* (Kodiak), *Ectocarpus commensalis* (Ketchikan, Sitka), *Punctaria latifolia* (Ketchikan, Sitka), *Scytosiphon lomentaria* (Ketchikan, Kodiak, Sitka), *Ceramium cimbricum* (*C. sungminbooi*?) (Ketchikan, Sitka), and *Palmaria mollis* (*P. palmata* (auct. japon.)) (Kodiak—this species is not native to Japan). All of these species have long been recognized as part of the seaweed flora of Pacific North America (Scagel et al., 1989).

A number of species listed as occurring on JTMD in Oregon or Washington were found on natural beaches we visited, including *Ulva linza* (Ketchikan), *Analipus japonicus* (Sitka), and cf. *Petalonia zosterifolia* (Kodiak). *Ulva linza* and *Analipus japonicus* have long been recognized in the local floras. The identity of the specimen tentatively called *Petalonia zosterifolia* is pending; it has also been recognized in the local flora previously, albeit not in the area covered by Scagel et al. (1989).

Long-term monitoring

Based on our observations, we concluded that the piers in Sitka, Alaska, and Westport in Grays Harbor, Washington, are suitable sites for long-term monitoring considering their accessibility, relatively rich macroalgal species diversity on the docks, and abundant arrival of JTMD to the area (Figure 14-1 and Figure 14-2). We made some surveys in natural habitats in Sitka and on Vancouver Island where a large amount of JTMD has been stranded, but because of dense populations of native macroalgal species, it would be difficult to recognize non-indigenous species if the population was small. A detailed account of the anatomy and distribution of each of the 80 (84) algal species is also provided online (Hansen, Hanyuda, and Kawai 2017a, b, c).

Grateloupia turuturu

Grateloupia livida

Pyropia yezoensis

Neodilsea yendoana

Mutimo cylindricus

Identification guide of seaweeds on Japanese tsunami debris

...ia pinnatifida

Chondrus yendoi

Ulva pertusa (=U. australis)

Scytosiphon gracilis

Field identification guide on NIS algae associated with JTMD (available at http://www.research.kobe-u.ac.jp/rcis-kurcis/KURCIS/FieldGuide2017may14LR.pdf).

Discussion

Through the field surveys of selected natural populations from Alaska to Oregon, we did not find any introduced populations that could be conclusively traced to JTMD. This may be because of the short time period after these possible introduction events.

The majority of the JTMD algae species (61%) are already present on the coasts of Pacific North America (see Chapter 9), but if haplotypes of these resident species differ from those on debris (e.g., *Petalonia*), there is still a substantial risk of genetic contamination (see Chapter 10). To date, no new populations of JTMD algal species have been found in any of the surveyed sites in Alaska, British Columbia, Washington State, or Oregon. Time, careful field surveys, and molecular screening are required if we are to fully understand the true impact of the JTMD algae in Pacific North America. The long-term monitoring sites we have selected will be helpful in detecting new introductions if they ever occur on these coasts.

Acknowledgements

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Pyropia sp.

Lindstrom (2018).

Chapter 14 Appendix

Appendix 14-1. Algae species observed in field surveys of British Columbia and Alaska

Appendix 14-1. Algae species observed in field surveys of British Columbia and Alaska

Group	Field observed species	Bamfield	Ucluelet	Tofino	Prince Rupert	Ketchikan	Sitka	Kodiak
Browns	*Costaria costata*				1			
Browns	*Desmarestia ligulata*			1				
Browns	*Desmarestia viridis*							1
Browns	*Ectocarpus commensalis*					1	1	
Browns	*Fucus distichus*				1			
Browns	*Hedophyllum nigripes*			1	1		1	1
Browns	cf. *Hincksia* sp(p).	1	1		1	1	1	
Browns	*Leathesia marina*	1						1
Browns	*Nereocystis luetkeana*				1			1
Browns	*Punctaria latifolia*					1	1	
Browns	*Saccharina latissima*					1		1
Browns	*Sargassum muticum**	1						
Browns	*Scytosiphon lomentaria*					1	1	1
Greens	*Acrosiphonia coalita*				1			
Greens	*Blidingia minima*			1		1		1
Greens	*Bryopsis* sp.	1			1			
Greens	*Chaetomorpha* sp.	1						1
Greens	*Cladophora* sp.	1	1		1	1	1	1
Greens	*Codium fragile* subsp. *californicum*	1					1	1 (drift)
Greens	*Derbesia marina*				1			1
Greens	*Percursaria percursa*				1			
Greens	*Prasiola meridionalis*				1			
Greens	*Rhizoclonium riparium*				1	1	1	1
Greens	*Ulva compressa*	1						
Greens	*Ulva fenestrata*	1	1	1	1	1	1	1
Greens	*Ulva intestinalis*		1	1	1	1		
Greens	*Ulva linza*				1	1		
Greens	*Ulva pertusa*	1						
Greens	*Ulva* cf. *prolifera*	1	1					1
Greens	*Ulva* spp.				1	1	1	1
Greens	*Ulvaria obscura* var. *blyttii*				1	1		1

Appendix 14-1. Algae species observed in field surveys of British Columbia and Alaska (cont'd)

Group	Field observed species	Bamfield	Ucluelet	Tofino	Prince Rupert	Ketchikan	Sitka	Kodiak
Reds	*Antithamnionella spirographidis**			1				
Reds	*Ceramium cimbricum* (*C. sungminbooi?*)					1	1	
Reds	*Ceramium gardneri*				1			
Reds	*Ceramium kondoi**	1				1		
Reds	*Ceramium pacificum*	1				1		
Reds	*Chondracanthus corymbiferus*	1		1				
Reds	*Erythrotrichia carnea*				1	1	1	1
Reds	cf. *Grateloupia californica*	1						
Reds	*Hymenena* sp.			1				
Reds	*Mazzaella oregona*			1		1		
Reds	*Mazzaella splendens*			1				
Reds	*Membranoptera platyphylla*			1				
Reds	*Microcladia coulteri*	1		1				
Reds	*Palmaria mollis* (*P. palmata* (auct. japon.))							1
Reds	*Polysiphonia brodiei**	1	1	1		1	1	
Reds	*Polysiphonia hendryi*	1		1				1
Reds	*Polysiphonia* cf. *senticulosa*							1
Reds	*Prionitis sternbergii*	1						
Reds	*Pyropia perforata*			1				
Reds	*Scagelia occidentale*				1	1	1	1
Total species		**19**	**6**	**15**	**20**	**20**	**14**	**21**
JTMD species		**7**	**5**	**3**	**8**	**12**	**8**	**10**

* Believed to be introduced species.
Highlighted rows represent species also observed on JTMD.


Kobe University

Charles Moore

THEME VI – Risk of Invasion

Chapter 15: The invasion risk of species associated with Japanese Tsunami Marine Debris in Pacific North America and Hawaii[1]

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Abstract

Marine debris from the Great Japan Tsunami of 2011 represents a unique transport vector for Japanese species to reach Pacific North America and Hawaii. The invasion risk of invertebrate species associated with tsunami debris was characterized using a screening-level risk assessment tool – the Canadian Marine Invasive Screening Tool (CMIST). Higher-risk invertebrate invaders were identified for each of five different ecoregions. Some of these species are well-known global invaders, such as the mussel *Mytilus galloprovincialis* and the ascidian *Didemnum vexillum* which already have invasion histories in several of the assessed ecoregions. Others, like the sea star *Asterias amurensis* and the shore crab *Hemigrapsus sanguineus,* also are recognized global invaders but have yet to invade large portions of the assessed ecoregions. In general, the probability of invasion was lower for the Gulf of Alaska and Hawaii, in part due to lower climate matches and the availability of other invasion vectors.

Introduction

On March 11, 2011, a 9.0 magnitude earthquake struck off the coast of Honshu, Japan, creating a devastating tsunami that reached heights of up to 40 m and inundated 562 km^2 in northern Japan (Mori et al., 2011). This tsunami sent millions of tons of Japanese Tsunami Marine Debris (JTMD) from terrestrial and coastal environments into the ocean (MoE, 2012). Although the specific types (wood, plastic, vessels, etc.) and origins of the resulting debris field were not quantified, it is clear that many objects were colonized by Japanese coastal species (Carlton et al., 2017). While the rafting of organisms on marine debris is not a new phenomenon and likely has been occurring for eons, especially on terrestrial and marine vegetation (Lewis et al., 2005; Thiel and Gutow, 2005), human-mediated activities have drastically increased the amount of debris in our oceans (Barnes, 2002; Gregory, 2009; Rech et al., 2016), dominated by plastic which does not readily biodegrade like plant material. A number of recent studies have identified a wide variety of taxa that are able to colonize marine debris. For example, Goldstein et al. (2014) documented 95 taxa from 11 phyla on plastic debris in the North Pacific Ocean. Although marine debris can remain at sea for considerable periods of time, especially if entrained into the North Pacific Gyre (i.e., "garbage patch"; e.g., Moore et al., 2001), a portion will eventually come ashore in coastal ecosystems, and these landings have the potential to deliver non-indigenous species (NIS) to novel locations.

Debris landings in Pacific North America and Hawaii associated with the Great Japan Tsunami of 2011 that include rafting of potential NIS from Japan could result in new invasions, some of which may lead to ecological and economic impacts (i.e., high-risk invaders). This would be consistent with marine invasions globally where a subset of established NIS becomes truly invasive (e.g., Williamson, 1996). Invasive species cost countries billions of dollars each year and often are identified as the second greatest threat to native biodiversity after habitat loss (Williamson, 1996; Sala et al., 2000; Colautti et al., 2006). Further, the direct negative impacts of biological invasions on fisheries and aquaculture operations are well documented, and there is growing evidence that invasive species have the ability to alter ecosystem function, negatively affecting native species/communities, and reducing the ecological integrity of these native systems (e.g., Bax et al., 2003; Colautti et al., 2006). Thus, given this unique event, it is important to identify potential NIS associated with JTMD that could pose a higher risk to coastal ecosystems in Pacific North America (California to Alaska) and Hawaii.

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[1] A version of this chapter was published in a special issue of *Marine Pollution Bulletin* (2018), 132: 82-89.

A variety of tools have been developed to evaluate the risk a species poses to a given area, using different combinations of factors thought to influence invasion success (reviewed in Kumschick and Richardson, 2013). Risk scoring schemes can provide a relatively quick way to screen and rank species without conducting time- and data-intensive quantitative risk analyses (e.g., Therriault and Herborg, 2007; Leung et al., 2012). Thus, they can be used to inform NIS management by rapidly screening a large number of species, allowing limited resources to be directed towards those NIS posing the greatest risk. Screening-level tools for NIS are generally based on the answers to a series of questions to determine if a species is a threat (high-risk) or not. The most common screening-level tool types are either decision trees (Reichard and Hamilton, 1997; Kolar and Lodge, 2002; Caley and Kuhnert, 2006) or scoring systems (Pheloung et al., 1999; Daehler et al., 2004; Copp et al., 2009; Drolet et al., 2016). Although decision trees work well in situations related to import (i.e., allow or not allow), scoring systems permit ranking of species based on perceived risk thereby providing a prioritized list of NIS for potential management intervention or policy development. All of these assessment tools rely on some understanding of the species (biology, tolerances, etc.) and previous invasion history (if available) in order to identify those NIS most likely to become invasive in the risk assessment area. Thus, data-poor NIS can be more challenging to assess independent of the tool applied, especially those lacking any prior invasion history since most high-risk invasive species were not predicted to be high-impact invaders until they resulted in substantial impacts elsewhere.

To inform potential monitoring, management or policy development around Japanese species arriving on JTMD, a risk assessment method that allows prioritization is desired. A recently developed marine screening-level risk assessment tool for NIS, the Canadian Marine Invasive Screening Tool (CMIST), follows the sequence of events in the invasion process: arrival, survival, establishment, spread, and impact. CMIST uses 17 generalized and non-taxon specific questions (Drolet et al., 2016) related to both the invasion process and a species' potential impact. Further, CMIST uses Monte Carlo simulation to allow uncertainty to be captured explicitly in the risk assessment score. This tool recently was applied to characterize the invasion risk of *Didemnum vexillum* in Atlantic Canada (Moore et al., 2018), and here we applied CMIST to species associated with JTMD to characterize the relative risk posed to Pacific North American and Hawaiian ecosystems. Specifically, we focused on invertebrates, of which more than 300 taxa have been identified in association with JTMD items thus far (Carlton et al., 2017).

Methods

Species associated with JTMD

Over 600 confirmed JTMD objects (based on multiple lines of evidence presented in Carlton et al., 2017) arriving on the shores of Pacific North America and Hawaii were opportunistically sampled for invertebrate, algae, and fish species since June 2012 (when JTMD began arriving en masse). Of the invertebrates associated with JTMD, five groups (mollusks, annelids, cnidarians, bryozoans, and crustaceans) composed 85% of the species diversity (Carlton et al., 2017). Although interception and sampling of JTMD items continues, our assessment of JTMD species risk is limited to those identified as of May 2016, given ongoing taxonomic revisions for many groups of organisms. Biological samples were processed morphologically, with genetic verification for some organisms, and identified to the lowest taxonomic level possible. All invertebrates identified to the species level were retained for screening for potential invasion risk (*N* = 131; 36 molluscs, 35 crustaceans, 18 bryozoans, 15 annelids, 13 cnidarians, 5 echinoderms, 2 nemerteans, 1 tunicate, and 6 others) while others were not assessed here because higher-level taxonomic information confounds the environmental tolerances, life history characteristics, and potential impacts of an organism, rendering risk scores less informative. A literature search and review was conducted for each species generating a database that included information on invasion history, native range, introduced range, environmental tolerances, and life history characteristics. Initial search terms included species/taxonomic names and then targeted data gaps more specifically (e.g., reproduction, temperature, distribution, etc.). This information came from a variety of sources (e.g., primary publications, reports, databases, internet searches, etc.) in both the international (English) and Japanese literature. Approximately 1,600 papers, six reference books, and up to 17 websites formed the basis for this literature search that resulted in a database[2] that was used in the risk assessment.

CMIST risk assessment

The potential risk of JTMD species arriving to Pacific North America and Hawaii was determined using CMIST. CMIST was developed based on the different steps in the invasion process (Drolet et al., 2016) and explicitly distinguishes the two risk components: 'Likelihood of Invasion' and 'Impact of Invasion' (Kumschick and Richardson, 2013). There are 17 CMIST questions and each of them is scored on a scale between 1 and 3 ("Low" = 1 to "High" = 3) (Drolet et al., 2016, Table 1). A mean score is calculated for the Likelihood of Invasion (i.e., questions 1–8) and Impacts of Invasion (i.e., questions 9–17), and these scores are then multiplied to obtain an overall relative risk score ranging from 1 to 9. In addition to answering each risk question, assessors also assign a qualitative uncertainty score ("Low certainty" = 1 to "High certainty" = 3) for each question. This uncertainty largely reflects the quality of information available and its interpretation when answering the CMIST questions. Potential uncertainty imposed via the CMIST tool itself (i.e., linguistic uncertainty sensu Regan et al., 2002) is generally addressed in the guidance document for CMIST application[3], and discussions among assessors prior to species screening reduced inter-assessor variability. The question answers and associated uncertainty ranking are used in a Monte Carlo randomization procedure to generate an adjusted risk score that includes uncertainty (Drolet et al., 2016). Although risk assessment tools tend

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[2] https://invasions.si.edu/nemesis/jtmd/searchTaxa.jsp

[3] http://www.bio.gc.ca/science/monitoring-monitorage/cmist/usage-en.php

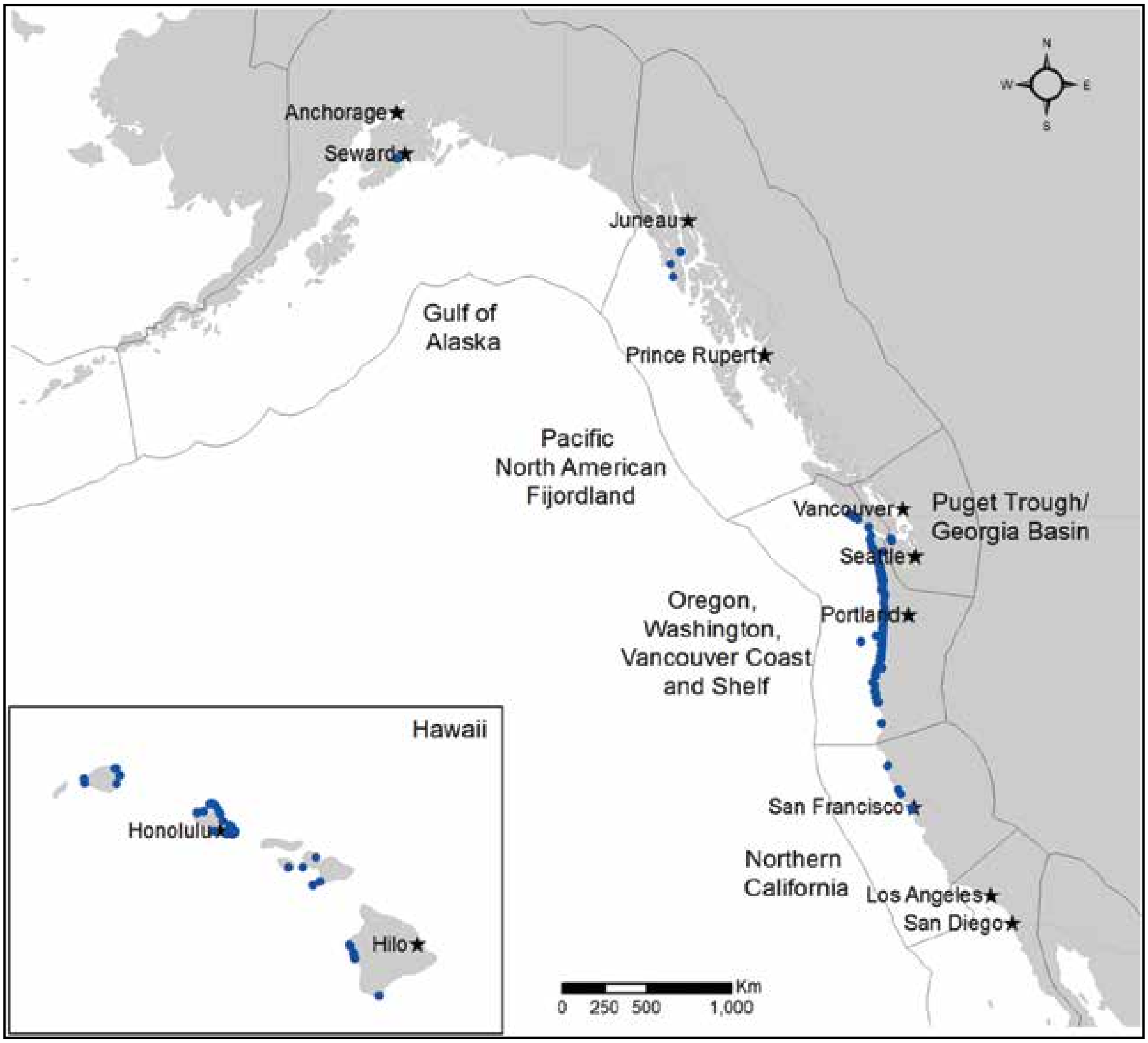

Figure 15-1. MEOW (Marine Ecoregions of the World) ecoregions of Pacific North America and Hawaii showing JTMD landings (blue solid circles) used in this study. Major cities (stars) are shown for reference.

to be over-parameterized (e.g., Gordon et al., 2008; Koop et al., 2012), including CMIST (Drolet et al., 2017), there was no basis in the application of CMIST to JTMD organisms that would allow a meaningful evaluation of individual question contributions or weighting (i.e., since these species have not invaded there is no independent basis for comparing model performance). Thus, all 17 questions were retained and scored. One minor modification was made to the original scoring rubric: Question 17 (Is the species known or generally considered to be invasive anywhere in the world?) originally stated "No, but has traits related to invasion" for scoring level 2, but was revised to state "No, but it has been noted outside of its native range" in order to account for species with limited information available that have moved beyond their native range and do not have recorded impacts.

Risk scores for NIS invertebrate species known to have been associated with JTMD were calculated by two assessors independently using CMIST in conjunction with the life history database, with a random subsample scored by a third assessor to check for consistency. These scores were then averaged to obtain the final risk score for each species–ecoregion combination. All assessors were knowledgeable about marine invasions (but not practicing risk assessors). Each assessor used the species literature database and their own knowledge of invasions and marine species to score each JTMD species for each of the five ecoregions in the eastern North Pacific that were known to have received JTMD (Figure 15-1): (1) Gulf of Alaska; (2) Pacific North American

Fijordland; (3) Oregon, Washington, Vancouver coast and shelf; (4) northern California; and (5) Hawaii (based on the Spalding et al. (2007) Marine Ecoregions of the World (MEOW) classification system). Each species was assessed for each ecoregion, though not all species were sampled from each ecoregion due to the potential that species may have arrived in any of the ecoregions but were not detected during the opportunistic sampling events. The Strait of Georgia/Puget Sound ecoregion was not included because we did not receive any confirmed reports of JTMD, and oceanographic models suggest that this region would not be expected to receive JTMD directly (Maximenko et al., 2012; Lebreton and Borreo, 2013). However, this region is connected by a myriad of vectors to other ecoregions along the Pacific coast of North America such that JTMD-associated species could indirectly arrive to the Strait of Georgia/Puget Sound ecoregion. To facilitate risk assessment, background information including ecosystems and habitat types present, sea surface temperature range, extent of species transport vectors operating in the region, and presence of species-at-risk was compiled for each of the ecoregions for which assessments were to be undertaken, and life history/invasion impact data were gathered for species associated with JTMD. Guidelines created by the CMIST developers provided further context for the screening tool questions (Drolet et al., 2016). Consistent with the intended application of CMIST, justification and sources of information used to answer each question were noted for each entry. The lower and upper 95% confidence intervals around the medians of the combined invertebrate species per ecoregion were reported. The effects of ecoregion and inter-assessor variability were assessed using the Repeated Measures General Linear Model for all taxa.

Results

There was no significant difference between assessors (*F* = 3.106, *p* = 0.07) and therefore, Monte Carlo adjusted risk scores were averaged across assessors. For the 131 species associated with JTMD assessed here, CMIST scores ranged from approximately 1.99 (lower risk) to 6.86 (higher risk) depending on the species and the ecoregion (Figure 15-2; Appendix 15-1). Although specific risk thresholds have not been identified for CMIST, the tool was able to provide a relative risk ranking for each JTMD species assessed. The higher-risk species (relative to other species scored from JTMD) among all ecoregions were well-known global invaders including the mussel *Mytilus galloprovincialis* (e.g., Branch and Steffani, 2004), the ascidian *Didemnum vexillum* (e.g., Coutts and Forrest, 2007), the crab *Hemigrapsus sanguineus* (e.g., Klassen, 2012), and the sea star *Asterias amurensis* (e.g., Hayes et al., 2005; Figure 15-2). In addition, plotting CMIST adjusted Likelihood of Invasion and adjusted Impact of Invasion scores (Figure 15-3) allows the identification of those higher-risk species that have both high likelihood of invasion and impacts (i.e., the upper right quadrant of these figures).

Table 15-1. Summary statistics of the entire suite of non-indigenous species (NIS) scored. Native species scores were excluded for each ecoregion. Cumulative risk refers to the sum of all risk scores for the ecoregion and per capita risk is the cumulative risk divided by *N*, the number of species included for each ecoregion.

Region	Median	Lower 95% CI	Upper 95% CI	Cumulative risk	Per capita risk	Min score	Max score	*N*
Gulf of Alaska	2.69	2.58	2.76	326.30	2.84	1.99	5.78	115
Pacific North American Fijordland	2.71	2.60	2.77	343.86	2.89	1.99	6.03	119
Oregon, Washington, Vancouver coast and shelf	2.72	2.61	2.84	315.37	3.00	2.00	6.62	105
Northern California	2.76	2.66	2.86	349.60	3.04	2.15	6.86	115
Hawaii	2.73	2.66	2.81	371.60	2.93	2.14	5.82	127

Overall, northern California had the highest median, per capita, and individual maximum and minimum risk scores (Table 15-1). Adjusted CMIST risk scores were significantly different by region (Figure 15-2; repeated measures GLM: *F* = 30.240, *p* < 0.001). Hawaii had the highest cumulative risk (species risk summed across all species) due to the highest number of species associated with JTMD that were not native to that region (127) and therefore, the highest number of potential invasions rather than higher risk species on average. In contrast, Oregon, Washington, Vancouver coast and shelf had the lowest cumulative risk due to fewer novel JTMD-associated species for that region. Although we do not know the total number of JTMD arrivals per ecoregion, it appears the Oregon, Washington, Vancouver coast and shelf area received substantially more objects (based on reports/collections recognizing potential bias; Figure 15-1) than the other ecoregions (Clarke Murray et al., 2018). Also, each ecoregion had different levels of invasion history, with some of the JTMD species already having been introduced by other vectors (Figure 15-2). In fact, of the higher-risk invertebrate species assessed using CMIST, the number of existing invaders in the five assessed ecoregions ranged from 15 in northern California to 8 in Hawaii (open diamonds in Figure 15-2), recognizing that not all of these species are necessarily distributed throughout the entire ecoregion they are present in. For each ecoregion, *M. galloprovincialis, D. vexillum*, and *H. sanguineus* consistently were identified as the highest risk invaders independent of these species being either previously present or absent from these ecoregions (Figure 15-2).

Discussion

A large diversity of non-indigenous species reached the Pacific North American and Hawaiian coasts via rafting

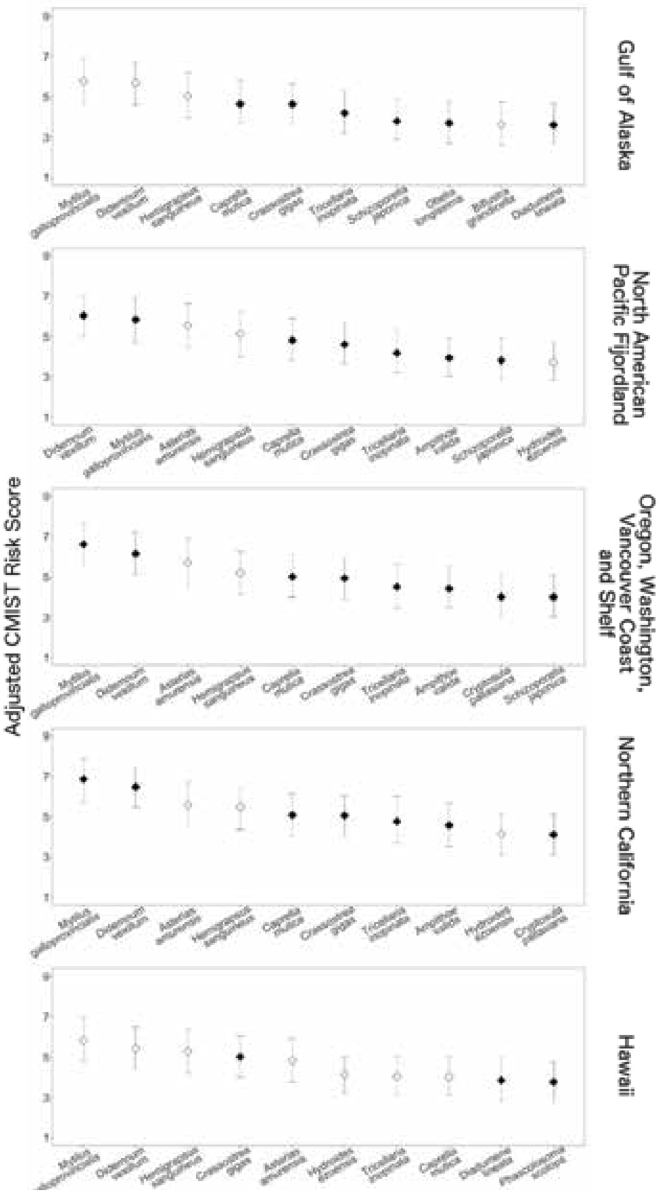

Figure 15-2. The ten highest risk invertebrate species by ecoregion: Gulf of Alaska, Pacific North American Fijordland, Oregon, Washington, Vancouver coast and shelf, northern California, and Hawaii. Error bars are 95% confidence intervals derived from the Monte Carlo simulation that includes assessor uncertainty. Solid diamonds denote non-native species already present in the ecoregion prior to JTMD arrival while open diamonds denote non-native species not already present in the ecoregion.

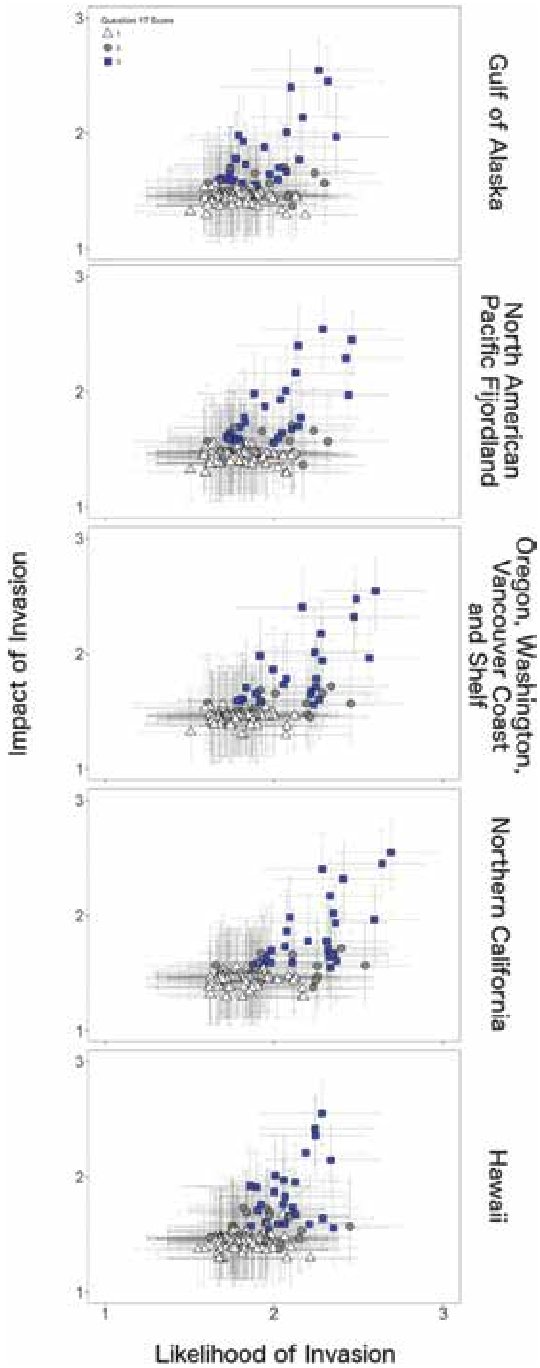

Figure 15-3. CMIST (Canadian Marine Invasive Screening Tool) scores decomposed into the two component scores, Impact of Invasion (*y*-axis) and Likelihood of Invasion (*x*-axis) for the 131 invertebrate species assessed for each of the five ecoregions (Gulf of Alaska, Pacific North American Fijordland, Oregon, Washington, Vancouver coast and shelf, northern California, and Hawaii). Error bars represent the uncertainty intervals derived from the Monte Carlo procedure that includes assessor uncertainty. Species include those that are known to be invasive elsewhere (solid blue squares), not known to be invasive elsewhere (open triangles), and those observed outside their native range (solid grey circles) as scored in CMIST Question 17.

on JTMD, including species with well-documented global invasion histories and documented impacts (e.g., *Mytilus galloprovincialis*, *Didemnum vexillum*, *Asterias amurensis,* and *Hemigrapsus sanguineus*). Of the species assessed, molluscs and crustaceans were common on JTMD – a finding consistent with other studies that have found these taxonomic groups entrained in other NIS vectors (e.g., Ruiz et al., 2015). Many of these species also have been introduced to other ecoregions around the world by a variety of human-mediated invasion vectors including commercial and recreational vessels and via aquaculture-mediated movements. Although some NIS have already established in our focal ecoregions prior to JTMD arrival via other invasion vectors, newly arriving individuals of the same species on JTMD may pose additional risks (see Hanyuda et al., 2018). For example, Roman and Darling (2007) showed that additional genetic diversity acquired via multiple introduction events can result in increased invasion success by avoiding potential genetic bottlenecks. Also, Roman (2006) reported how a cryptic invasion by the European green crab *Carcinus maenas* in Atlantic Canada resulted in an increase in invaded range owing to different environmental tolerances between the initial invasion event and one about 100 years later. In general, the addition of new alleles to a population could result in increased environmental tolerances, fitness and ultimately invasion success (Roman, 2006; Geller et al., 2010).

Two advantages of the CMIST tool as applied here included: (1) the explicit incorporation of uncertainty in the risk score and (2) the reliance on fewer questions to be answered compared to other screening-level risk assessment tools (Drolet et al., 2016) recognizing that even with only 17 questions CMIST may be over-parameterized (Drolet et al., 2017) – an issue faced by other risk assessment tools (e.g., Gordon et al., 2008; Koop et al., 2012). As with all risk assessments, readily available information is critical. The application of CMIST to JTMD species that were either well-known or recognized high-impact invaders (e.g., *Mytilus* or *Didemnum*) worked well as we were able to screen a high volume of species in a relatively short period of time with readily available information as intended for a screening-level risk assessment process. However, perhaps not surprisingly, for this assessment overall there was considerable variation in available literature among JTMD species assessed. Despite our efforts to include the Japanese literature for JTMD species assessed, we recognize additional literature might be available for some species that could reduce uncertainty in future assessments. As CMIST was applied here, species that had not been previously reported outside their native range or lacked documented impacts in the literature scored lower overall (see below) and thus risk may have been underestimated. By design, the CMIST scoring rubric relies on the best available information (Drolet et al., 2016) and, despite the potential over-parameterization (i.e., some questions not informative with respect to invasion risk; Drolet et al., 2017), additional sensitivity analyses would be required to determine thresholds for tool application. In addition, taxonomic resolution was required to apply CMIST so only those species with fully ascribed binomials were assessed with the tool such that organisms only resolved to higher taxonomic levels (i.e., genus or family) were not screened, including some that could be higher risk to North American ecosystems. Another taxonomic issue is not recognizing a NIS when present such that impacts are attributed to native "pests" simply due to poor taxonomy. Thus, although molecular approaches might help to identify these NIS when co-occurring with native congeners, it likely will remain a challenge attributing impacts to them such that they appear more benign than they really are.

There were many species on JTMD that were data limited either due to a lack of study (e.g., biology, environmental tolerances) or lack of previous invasion history (e.g., invasion vectors, impacts) which often resulted in these species receiving lower scores in our application of CMIST. By design, CMIST questions must be scored (i.e., cannot be left blank or "0") using higher level taxonomic or more general information/data if required, but this is partially offset by the higher uncertainty scores for these species that get incorporated into the adjusted risk score. The invasion probability questions in CMIST are related to the potential for species to arrive, survive, reproduce, and spread, based on the known history of the species. With the exceptions of Hawaii (too warm for some species) and Gulf of Alaska (too cold for some species), most of the species assessed here had relatively good climate match between the source location in Japan and the receiving environments along the Pacific coast of North America from Pacific North American Fijordland to northern California. Of the five ecoregions assessed, northern California arguably has the highest climate/habitat match to the Tohoku region of Japan where most JTMD species are believed to have originated. However, since many of these species are not known from other invasion vectors (Carlton et al., 2017) despite general taxonomic association with other invasion vectors (i.e., Ruiz et al., 2015, as >50% of assessed JTMD species were molluscs or crustaceans), they would have scored lower in our application of CMIST for arrival and spread questions, which include all invasion vectors despite potentially scoring higher for survival and reproduction potential. Each question is weighted equally in the overall score, which means these survival and reproduction questions only counted for a small fraction of the score (3 out of 17 questions). Also, since many of the species that originated from Japan have no previous reports outside their native range, their potential impacts were scored lower in our assessment.

Assessing the potential impacts of species with no prior invasion history also remains a challenge despite efforts to predict impacts (e.g., Blackburn et al., 2014; Ojaveer et al., 2015). Further, even where invasions are well documented, the impacts for the majority of known marine species have not been evaluated, leading to an absence of data for risk assessments (Ruiz et al., 1999; Ruiz et al., 2011a). In our application of CMIST, the lack of demonstrated impacts were scored as "1" or "Low" assuming there were no closely related species with documented impacts. Thus, these species are being treated as "innocent until proven guilty" (sensu Azmi et al., 2015). However, recognizing this is not the most precautionary approach, assuming a higher level of impact such as "Intermediate" (or "2" in CMIST) as suggested by Azmi et al. (2015) (and adjusting the impact scores for the species with information accordingly)

would then result in universally inflated CMIST scores in this context where many species encountered on JTMD lack any prior invasion history, ultimately resulting in a longer list of potentially risky species to watch for. Thus, the highest risk species identified here were well-known invaders with previously documented, significant impacts in other parts of the world, like *M. galloprovincialis* and *D. vexillum*. While past invasion history is often the best available predictor of future impacts (e.g., Reichard and Hamilton, 1997; Boudouresque and Verlaque, 2002), there exist many examples where a species' introduction has had unexpected/unpredicted impacts based on its earlier invasion history or lack thereof. Unfortunately, only time will tell if such a species reaches Pacific North America or Hawaii on JTMD. More importantly, the lack of scientific evidence of impacts does not equal no impact – something that needs to be clearly communicated to managers and policy makers.

Overall, risk varied by region, with northern California having the highest median and per capita risk scores among ecoregions and the Gulf of Alaska having the lowest. Northern California also had the highest minimum and maximum CMIST scores for individual species, further highlighting the risk JTMD species could pose. This is perhaps not surprising given that the northern California ecoregion includes San Francisco Bay which has a well-documented invasion history (e.g., Cohen and Carlton, 1998; Cox, 1999; Ruiz et al., 2011b). Hawaii also has a substantial number of invasive species (e.g., Carlton and Eldredge, 2009, 2015), and our analyses showed that Hawaii had the largest number of novel JTMD species, hence cumulative risk (summed over these species) was highest but the per capita risk was lower possibly due to the less favourable climate match between Japan and this ecoregion. In Oregon, Washington, Vancouver coast and shelf and Pacific North American Fijordland, 7 of the 10 highest risk species have already been introduced by other vectors. In contrast, Hawaii is relatively less invaded by these species, with only 3 of the 10 highest risk species already present.

The differing risks reflect the different invasion vectors, habitat types, and climate matches to donor ecoregions and invasion hotspots like San Francisco Bay (Ruiz et al., 2011b). For example, the survival and establishment of a species in a new ecoregion is an important and limiting step in the invasion process (e.g., Gollasch, 2002; Blackburn et al., 2011). Here, as in other risk assessments, we used empirically-derived temperature and salinity thresholds where known, and native range environmental proxies otherwise. These environmental thresholds are not strict limits and do not account for plasticity and adaptation that are commonly seen in invasive species (e.g., Sakai et al., 2001). In addition to the part the physical and chemical receiving environment plays, the native biological community also plays a role in determining invasion success. In CMIST, two of the 17 questions refer to temperature and salinity tolerances pertaining to survival and reproduction, while a third question refers to availability of suitable habitat. In contrast to some other risk assessment tools where climate match can lead to zero probability of introduction (e.g., Gollasch and Leppäkoski, 2007), there are no zero rankings with CMIST and the species are ranked on a qualitative scale. Therefore, overestimation may occur where tropical species could be ranked higher risk in arctic areas even though the probability of survival might be very low. This represents a trade-off applying screening-level risk assessment tools compared to more specific detailed-level risk assessment tools.

In addition to the documented free-living invertebrate NIS on JTMD thus far, parasite and disease organisms entrained with JTMD or its associated species that would otherwise lack a potential invasion vector could pose additional risks to Pacific North American ecosystems. The high-risk species *M. galloprovincialis* and its hydroid parasite *Eutima* were both detected on JTMD objects (Calder et al., 2014; G. Ruiz, unpublished data) and assessed here. While the risk of known parasites and associated species is addressed in one question of CMIST, the data on parasite diversity for many invertebrate groups remain limited and, where present, there is often considerable uncertainty about the potential consequences of parasites and diseases. Also, a number of parasites have complex life history strategies requiring multiple hosts to complete their life cycle. It is possible that newly arriving JTMD species could serve as intermediate and/or final hosts for parasites or diseases that might be arriving to the same area by other vectors (e.g., ballast water), allowing previously unsuccessful invasions to succeed. A similar unexpected consequence occurred with the historical transport of Pacific oyster *Crassostrea gigas* and Atlantic oyster *Crassostrea virginica*, where entire oyster communities were imported to Pacific North American coastal ecosystems for aquaculture production, thereby allowing a number of hitchhiking organisms to be moved as well. These movements have been implicated in the establishment of many species along the Pacific coast. For example, several NIS were introduced with oysters to California (Carlton, 1979; Ruiz et al., 2011a) and to British Columbia (Levings et al., 2002; Gillespie, 2007; Daniel and Therriault, 2007), including a number of high-impact species such as the oyster drills *Urosalpinx cinerea* and *Ocinebrellus inornata*.

The application of CMIST to JTMD species confirmed the presence of high-risk NIS on JTMD objects: two JTMD species (*A. amurensis* and *M. galloprovincialis*) are among the International Union for the Conservation of Nature's (IUCN) world's worst invasive species (Lowe et al., 2000). It is important to note that some of this risk could be reduced through mitigation actions. For example, intervention that removes fouled JTMD items immediately following detection from beaches or adjacent coastal waters can decrease the risk of invasion by reducing the propagule load to native ecosystems, which can lower establishment success of many NIS (sensu Simberloff, 2009). Given the time lag in invasion population dynamics (Crooks and Soulé, 1999) and detection thresholds (Fagan et al., 2002; Neubert and Parker, 2004; Regan et al., 2006; Rout et al., 2009), monitoring in the coming decades is warranted, especially for those higher-risk species identified here.

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Chapter 15 Appendix

Appendix 15-1. Species by ecoregion showing breakdown of risk scores

Appendix 15-1. Species by ecoregion showing breakdown of risk scores

				Gulf of Alaska								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Annelida	*Amblyosyllis speciosa*		2	1.15	1.50	1.89	1.33	1.69	2.13	1.72	2.52	3.50
Annelida	*Arabella* sp. *semimaculata*-group	i	1	1.11	1.46	1.89	1.41	1.81	2.25	1.78	2.64	3.73
Annelida	*Eulalia quadrioculata*		1	1.11	1.49	1.89	1.50	1.85	2.21	1.93	2.76	3.79
Annelida	*Eulalia viridis*-complex		1	1.11	1.42	1.78	1.37	1.77	2.13	1.81	2.49	3.38
Annelida	*Halosydna brevisetosa*		1	1.11	1.46	1.85	1.58	1.98	2.34	2.04	2.87	3.90
Annelida	*Harmothoe imbricata*		1	1.17	1.46	1.83	1.79	2.13	2.44	2.33	3.10	4.06
Annelida	*Hydroides ezoensis*		3	1.67	1.98	2.33	1.50	1.79	2.13	2.67	3.53	4.47
Annelida	*Nereis pelagica*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Perinereis nigropunctata*		1	1.11	1.45	1.86	1.32	1.72	2.17	1.72	2.51	3.48
Annelida	*Pygospio californica*		1	1.11	1.46	1.89	1.46	1.86	2.29	1.86	2.72	3.81
Annelida	*Spirobranchus polytrema*		2	1.28	1.65	2.06	1.50	1.89	2.31	2.18	3.11	4.24
Annelida	*Syllis elongata*-complex		1	1.11	1.49	1.89	1.37	1.72	2.13	1.74	2.57	3.56
Annelida	*Syllis gracilis*-complex		1	1.11	1.49	1.89	1.31	1.65	2.07	1.67	2.46	3.46
Annelida	*Syllis hyalina*-complex		1	1.07	1.41	1.81	1.42	1.75	2.17	1.71	2.49	3.44
Annelida	*Trypanosyllis zebra*		1	1.11	1.46	1.83	1.24	1.59	2.00	1.59	2.32	3.22
Bryozoa	*Aetea anguina*		2	1.14	1.47	1.86	1.71	2.09	2.46	2.21	3.07	4.07
Bryozoa	*Arbocuspis* n. sp.	ii	1	1.22	1.53	1.95	1.25	1.63	2.06	1.68	2.49	3.50
Bryozoa	*Biflustra grandicella*		3	1.52	1.88	2.30	1.58	1.94	2.33	2.64	3.63	4.75
Bryozoa	*Biflustra irregulata*		1	1.11	1.46	1.89	1.50	1.90	2.31	1.98	2.78	3.78
Bryozoa	*Callopora craticula*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Cauloramphus spinifer*	iii	1	1.11	1.46	1.89	1.44	1.83	2.19	1.87	2.67	3.67
Bryozoa	*Celleporella hyalina*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Celleporina porosissima*		1	1.10	1.46	1.89	1.56	1.97	2.38	2.02	2.88	3.90
Bryozoa	*Cryptosula pallasiana*		2	1.37	1.71	2.07	1.66	2.06	2.38	2.63	3.52	4.58
Bryozoa	*Escharella hozawai*		1	1.11	1.46	1.89	1.44	1.85	2.25	1.87	2.71	3.76
Bryozoa	*Exochella tricuspis*		1	1.17	1.51	1.95	1.37	1.78	2.19	1.82	2.69	3.67
Bryozoa	*Membranipora villosa*	iv	1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Microporella borealis*		1	1.11	1.48	1.89	1.55	1.92	2.32	1.88	2.84	3.90
Bryozoa	*Schizoporella japonica*		3	1.44	1.78	2.15	1.79	2.15	2.50	2.90	3.80	4.92
Bryozoa	*Smittoidea spinigera*		1	1.11	1.46	1.89	1.50	1.87	2.25	1.88	2.72	3.75
Bryozoa	*Tricellaria inopinata*		3	1.63	2.01	2.37	1.71	2.07	2.46	3.19	4.20	5.28
Bryozoa	*Tubulipora masakiensis*		1	1.11	1.46	1.89	1.50	1.89	2.31	1.90	2.77	3.90
Bryozoa	*Tubulipora pulchra*		1	1.11	1.45	1.89	1.50	1.90	2.31	1.89	2.76	3.77
Chordata	*Didemnum vexillum*		3	2.15	2.45	2.75	2.00	2.32	2.64	4.62	5.70	6.73
Cnidaria	*Amphisbetia furcata*		1	1.07	1.41	1.82	1.37	1.77	2.17	1.74	2.50	3.41
Cnidaria	*Bougainvillia muscus*		3	1.22	1.55	1.96	1.50	1.89	2.21	2.14	2.95	3.97
Cnidaria	*Diadumene lineata*		2	1.22	1.57	1.97	1.96	2.30	2.63	2.70	3.61	4.67
Cnidaria	*Eutima japonica*		2	1.33	1.68	2.06	1.37	1.74	2.13	2.08	2.92	3.91
Cnidaria	*Halecium tenellum*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Hydrodendron gracilis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Metridium dianthus*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Obelia longissima*		2	1.33	1.65	2.04	1.87	2.24	2.59	2.71	3.70	4.75
Cnidaria	*Orthopyxis caliculata*		1	1.11	1.44	1.83	1.74	2.13	2.50	2.18	3.07	4.13
Cnidaria	*Orthopyxis platycarpa*	v	1	1.05	1.38	1.78	1.50	1.87	2.25	1.84	2.58	3.52
Cnidaria	*Plumularia setacea*		2	1.07	1.37	1.74	1.71	2.11	2.46	2.10	2.90	3.86
Cnidaria	*Pocillopora damicornis*		1	1.06	1.32	1.67	1.19	1.50	1.94	1.39	1.99	2.74
Cnidaria	*Sertularella mutsuensis*		1	1.05	1.38	1.78	1.19	1.61	2.06	1.53	2.23	3.12

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Gulf of Alaska								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
Group	**Species**	**Footnote**	**Invasion history score**	**Lower confidence limit**	**Mean**	**Upper confidence limit**	**Lower confidence limit**	**Mean**	**Upper confidence limit**	**Lower confidence limit**	**Mean**	**Upper confidence limit**
Crustacea	*Ampithoe lacertosa*		2	1.18	1.57	1.96	1.62	1.97	2.33	2.22	3.08	4.07
Crustacea	*Ampithoe valida*		3	1.59	1.93	2.30	1.46	1.82	2.21	2.63	3.51	4.55
Crustacea	*Balanus crenatus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus glandula*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus trigonus*		3	1.28	1.61	1.94	1.31	1.69	2.06	1.98	2.70	3.66
Crustacea	*Caprella cristibrachium*		1	1.11	1.46	1.89	1.19	1.63	2.06	1.58	2.38	3.34
Crustacea	*Caprella mutica*		3	1.63	1.97	2.34	2.04	2.37	2.67	3.71	4.65	5.82
Crustacea	*Caprella penantis*		3	1.33	1.64	1.96	1.62	1.97	2.33	2.40	3.24	4.31
Crustacea	*Chthamalus challengeri*		3	1.44	1.78	2.19	1.46	1.77	2.17	2.31	3.18	4.21
Crustacea	*Dactylopodamphiascopsis latifolius*		1	1.11	1.46	1.83	1.25	1.68	2.13	1.60	2.45	3.44
Crustacea	*Dynoides spinipodus*		1	1.11	1.46	1.89	1.31	1.71	2.19	1.67	2.49	3.56
Crustacea	*Gammaropsis japonica*		1	1.00	1.29	1.67	1.25	1.60	2.00	1.44	2.06	2.89
Crustacea	*Harpacticus compsonyx*	vi	1	1.11	1.46	1.83	1.31	1.67	2.13	1.67	2.45	3.33
Crustacea	*Harpacticus nicaeensis*		1	1.11	1.46	1.83	1.25	1.65	2.13	1.65	2.41	3.34
Crustacea	*Harpacticus septentrionalis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Harpacticus* sp. *-flexus* group	vii	1	1.11	1.46	1.89	1.37	1.75	2.19	1.72	2.56	3.65
Crustacea	*Hemigrapsus sanguineus*		3	2.07	2.40	2.71	1.70	2.10	2.46	3.97	5.04	6.21
Crustacea	*Heterolaophonte discophora*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Ianiropsis serricaudis*		3	1.26	1.60	2.00	1.67	2.02	2.42	2.31	3.24	4.32
Crustacea	*Jassa marmorata*-complex		3	1.33	1.70	2.11	1.70	2.03	2.38	2.51	3.44	4.50
Crustacea	*Megabalanus rosa*		3	1.33	1.65	2.06	1.37	1.74	2.13	2.11	2.88	3.89
Crustacea	*Megabalanus zebra*		3	1.22	1.59	2.00	1.25	1.66	2.06	1.83	2.65	3.66
Crustacea	*Oedignathus inermis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Paralaophonte congenera*		1	1.11	1.46	1.83	1.37	1.71	2.06	1.73	2.50	3.45
Crustacea	*Paramphiascella fulvofasciata*		1	0.99	1.37	1.78	1.31	1.68	2.06	1.62	2.30	3.21
Crustacea	*Parastenhelia spinosa*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Parathalestris intermedia*		1	1.11	1.46	1.89	1.50	1.90	2.31	1.96	2.78	3.78
Crustacea	*Pseudoctomeris sulcata*		2	1.22	1.57	2.01	1.25	1.61	2.06	1.74	2.53	3.59
Crustacea	*Sarsamphiascus minutus*		1	1.11	1.46	1.89	1.44	1.85	2.25	1.89	2.70	3.77
Crustacea	*Sarsamphiascus varians* group		1	1.11	1.45	1.89	1.25	1.62	2.06	1.57	2.35	3.43
Crustacea	*Semibalanus cariosus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Sphaerozius nitidus*		2	1.22	1.59	2.06	1.31	1.68	2.06	1.83	2.67	3.74
Crustacea	*Stenothoe crenulata*-complex		3	1.22	1.60	2.00	1.31	1.71	2.13	1.81	2.74	3.78
Crustacea	*Xestoleberis setouchiensis*		1	1.11	1.46	1.83	1.37	1.75	2.19	1.74	2.57	3.65
Crustacea	*Zeuxo normani*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Echinodermata	*Aphelasterias japonica*		1	1.17	1.54	1.95	1.44	1.78	2.19	1.91	2.74	3.75
Echinodermata	*Asterias amurensis*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Echinodermata	*Havelockia versicolor*		1	1.06	1.44	1.83	1.31	1.66	2.06	1.65	2.39	3.32
Echinodermata	*Patiria pectinifera*		1	1.11	1.43	1.83	1.43	1.74	2.13	1.75	2.48	3.42
Echinodermata	*Temnotrema sculptum*		1	1.17	1.52	1.94	1.25	1.59	2.01	1.60	2.42	3.40
Miscellaneous	*Cibicides lobatulus*	viii	1	1.00	1.29	1.67	1.87	2.18	2.50	2.08	2.81	3.72
Miscellaneous	*Endeis nodosa*		2	1.11	1.42	1.83	1.31	1.63	2.00	1.67	2.32	3.21
Miscellaneous	*Gromia oviformis*		1	1.00	1.29	1.61	1.75	2.07	2.44	1.94	2.67	3.60
Miscellaneous	*Halacarellus schefferi*		1	1.11	1.43	1.85	1.46	1.84	2.29	1.85	2.63	3.65
Miscellaneous	*Phascolosoma scolops*		3	1.33	1.70	2.06	1.37	1.74	2.19	2.12	2.94	3.88
Miscellaneous	*Telmatogeton japonicus*		3	1.28	1.60	2.00	1.44	1.74	2.06	2.01	2.77	3.66

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Gulf of Alaska								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Mollusca	*Arca navicularis*		1	1.05	1.38	1.78	1.31	1.65	2.06	1.58	2.30	3.26
Mollusca	*Bankia bipennata*		1	1.11	1.47	1.89	1.37	1.79	2.25	1.82	2.62	3.67
Mollusca	*Bankia carinata*		1	1.11	1.48	1.89	1.44	1.83	2.19	1.90	2.72	3.68
Mollusca	*Barbatia virescens*	ix	1	1.05	1.37	1.78	1.31	1.67	2.06	1.58	2.30	3.22
Mollusca	*Crassostrea gigas*		3	1.85	2.14	2.41	1.82	2.17	2.51	3.69	4.65	5.64
Mollusca	*Crepidula onyx*		3	1.40	1.73	2.08	1.42	1.83	2.21	2.27	3.14	4.12
Mollusca	*Dendostrea folium*		2	1.17	1.53	1.95	1.44	1.79	2.19	1.96	2.74	3.67
Mollusca	*Dendronotus frondosus*		1	1.11	1.33	1.67	1.68	2.04	2.38	2.03	2.72	3.63
Mollusca	*Dolabella auricularia*		1	1.06	1.39	1.78	1.50	1.83	2.25	1.80	2.54	3.44
Mollusca	*Hermissenda crassicornis*		1	1.17	1.43	1.78	1.62	1.99	2.38	2.08	2.84	3.67
Mollusca	*Hiatella orientalis*	x	2	1.11	1.45	1.78	1.75	2.08	2.44	2.19	3.01	4.06
Mollusca	*Hyotissa chemnitzi*		1	1.11	1.45	1.83	1.25	1.66	2.13	1.65	2.41	3.44
Mollusca	*Hyotissa numisma*		1	1.11	1.49	1.89	1.25	1.66	2.06	1.67	2.48	3.44
Mollusca	*Isognomon legumen*		1	1.05	1.38	1.73	1.31	1.68	2.13	1.58	2.33	3.27
Mollusca	*Laevichlamys irregularis*		1	1.11	1.46	1.83	1.31	1.73	2.19	1.71	2.53	3.60
Mollusca	*Limaria hakodatensis*		1	1.11	1.46	1.89	1.50	1.84	2.25	1.87	2.69	3.78
Mollusca	*Lithophaga curta*		1	1.11	1.43	1.83	1.25	1.63	2.06	1.59	2.33	3.33
Mollusca	*Lyrodus takanoshimensis*		3	1.22	1.57	1.94	1.50	1.81	2.19	1.99	2.84	3.78
Mollusca	*Mitrella moleculina*		1	1.11	1.45	1.83	1.37	1.72	2.13	1.67	2.50	3.44
Mollusca	*Mizuhopecten yessoensis*	xi	1	1.11	1.45	1.83	1.62	1.99	2.38	2.12	2.89	3.78
Mollusca	*Modiolarca cuprea*	xii	1	1.11	1.46	1.89	1.25	1.68	2.13	1.67	2.46	3.44
Mollusca	*Modiolus nipponicus*		1	1.05	1.37	1.73	1.31	1.75	2.13	1.65	2.42	3.47
Mollusca	*Mopalia seta*		1	1.11	1.48	1.89	1.50	1.87	2.25	1.91	2.77	3.76
Mollusca	*Mytilisepta virgata*	xiii	1	1.10	1.43	1.84	1.37	1.71	2.06	1.68	2.45	3.45
Mollusca	*Mytilus coruscus*	xiv	1	1.11	1.36	1.78	1.50	1.90	2.31	1.84	2.59	3.60
Mollusca	*Mytilus galloprovincialis*		3	2.22	2.55	2.83	1.87	2.27	2.57	4.68	5.78	6.95
Mollusca	*Mytilus trossulus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Nipponacmea habei*		1	1.11	1.49	1.89	1.37	1.75	2.19	1.79	2.60	3.65
Mollusca	*Pascahinnites coruscans*		1	1.11	1.48	1.89	1.37	1.73	2.13	1.75	2.56	3.64
Mollusca	*Pinctada imbricata*		1	1.11	1.43	1.78	1.25	1.59	2.00	1.57	2.28	3.13
Mollusca	*Reishia bronni*	xv	1	1.21	1.56	1.95	1.31	1.65	2.06	1.80	2.57	3.43
Mollusca	*Scaeochlamys squamata*		1	1.11	1.48	1.89	1.31	1.75	2.19	1.75	2.58	3.55
Mollusca	*Sphenia coreanica*		3	1.22	1.59	1.94	1.37	1.76	2.19	1.91	2.79	3.78
Mollusca	*Spondylus cruentus*	xvi	1	1.11	1.46	1.89	1.25	1.68	2.13	1.67	2.45	3.54
Mollusca	*Teredo navalis*		3	1.33	1.67	2.04	1.71	2.07	2.46	2.57	3.46	4.41
Mollusca	*Teredothyra smithi*		1	1.06	1.41	1.84	1.25	1.63	2.06	1.53	2.30	3.24
Nemertea	*Oerstedia dorsalis*		1	1.17	1.50	1.83	1.50	1.92	2.31	2.06	2.87	3.85
Nemertea	*Quasitetrastemma nigrifrons*	xvii	1	1.11	1.39	1.72	1.37	1.79	2.19	1.71	2.48	3.43

Now in JTMD list under name in column, but searched as:

i	*Arabella semimaculata*
ii	*Arbocuspis bellula*
iv	*Membranipora serrilamella*
vi	*Harpacticus pacificus*
xii	*Musculus cupreus*
xi	*Patinopecten yessoensis*
xiii	*Septifer virgatus*
xvii	*Tetrastemma nigrifrons*

In JTMD list under name in column, but referred to in marinespecies.org as:

iii	*Cauloramphus spiniferum* (Johnston 1832)
v	*Orthopyxis crenata* (Hartlaub 1901)
viii	*Lobatula lobatula* (Walker & Jacob 1798)
x	*Hiatella arctica* (Linnaeus 1767)
xiv	*Mytilus unguiculatus* (Valenciennes 1858)
xvi	*Spondylus squamosus* (Schreibers 1793)

Retained as name in column due to similarities in data, but searched as:

iii	*Cauloramphus cryptoarmatus*
vii	*Harpacticus flexus*
xv	*Reishia clavigera*
ix	*Barbatia foliata*

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				North American Pacific Fijordland								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Annelida	*Amblyosyllis speciosa*		2	1.15	1.50	1.89	1.37	1.69	2.08	1.76	2.52	3.51
Annelida	*Arabella* sp. *semimaculata*-group	i	1	1.11	1.47	1.89	1.50	1.88	2.29	1.87	2.77	3.83
Annelida	*Eulalia quadrioculata*		1	1.15	1.49	1.89	1.50	1.89	2.25	1.93	2.81	3.77
Annelida	*Eulalia viridis*-complex		1	1.11	1.42	1.84	1.37	1.77	2.13	1.74	2.51	3.47
Annelida	*Halosydna brevisetosa*		1	1.11	1.45	1.82	1.75	2.11	2.46	2.22	3.04	4.04
Annelida	*Harmothoe imbricata*		1	1.17	1.47	1.83	1.87	2.12	2.44	2.32	3.10	4.00
Annelida	*Hydroides ezoensis*		3	1.67	1.98	2.33	1.56	1.88	2.19	2.83	3.72	4.71
Annelida	*Nereis pelagica*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Perinereis nigropunctata*		1	1.15	1.46	1.85	1.37	1.73	2.13	1.76	2.54	3.52
Annelida	*Pygospio californica*		1	1.11	1.48	1.89	1.50	1.90	2.33	1.91	2.81	3.87
Annelida	*Spirobranchus polytrema*		2	1.28	1.65	2.06	1.56	1.93	2.32	2.26	3.17	4.24
Annelida	*Syllis elongata*-complex		1	1.11	1.49	1.89	1.50	1.83	2.19	1.87	2.72	3.68
Annelida	*Syllis gracilis*-complex		1	1.11	1.48	1.89	1.31	1.65	2.07	1.67	2.45	3.41
Annelida	*Syllis hyalina*-complex		1	1.07	1.41	1.82	1.54	1.88	2.33	1.87	2.66	3.63
Annelida	*Trypanosyllis zebra*		1	1.11	1.47	1.84	1.24	1.59	2.00	1.59	2.34	3.32
Bryozoa	*Aetea anguina*		2	1.18	1.47	1.85	1.75	2.12	2.46	2.25	3.11	4.17
Bryozoa	*Arbocuspis* n. sp.	ii	1	1.16	1.53	1.95	1.25	1.63	2.06	1.68	2.50	3.61
Bryozoa	*Biflustra grandicella*		3	1.48	1.87	2.30	1.58	1.95	2.33	2.64	3.62	4.74
Bryozoa	*Biflustra irregulata*		1	1.11	1.46	1.83	1.56	1.96	2.38	2.02	2.87	3.90
Bryozoa	*Callopora craticula*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Cauloramphus spinifer*	iii	1	1.11	1.46	1.83	1.37	1.79	2.19	1.81	2.60	3.65
Bryozoa	*Celleporella hyalina*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Celleporina porosissima*		1	1.10	1.46	1.89	1.56	1.97	2.38	1.98	2.88	3.90
Bryozoa	*Cryptosula pallasiana*		2	1.37	1.71	2.07	1.75	2.10	2.42	2.64	3.60	4.66
Bryozoa	*Escharella hozawai*		1	1.11	1.46	1.83	1.44	1.85	2.31	1.89	2.70	3.78
Bryozoa	*Exochella tricuspis*		1	1.11	1.52	1.95	1.44	1.78	2.19	1.87	2.71	3.69
Bryozoa	*Membranipora villosa*	iv	1	1.17	1.43	1.78	1.56	1.93	2.31	1.99	2.76	3.58
Bryozoa	*Microporella borealis*		1	1.11	1.48	1.89	1.50	1.92	2.32	1.97	2.84	3.99
Bryozoa	*Schizoporella japonica*		3	1.44	1.78	2.15	1.79	2.16	2.50	2.89	3.81	4.90
Bryozoa	*Smittoidea spinigera*		1	1.11	1.46	1.89	1.50	1.87	2.32	1.88	2.74	3.78
Bryozoa	*Tricellaria inopinata*		3	1.63	2.01	2.37	1.71	2.07	2.42	3.19	4.18	5.35
Bryozoa	*Tubulipora masakiensis*		1	1.11	1.46	1.89	1.50	1.89	2.31	1.92	2.77	3.78
Bryozoa	*Tubulipora pulchra*		1	1.11	1.46	1.90	1.56	1.93	2.38	1.96	2.83	3.90
Chordata	*Didemnum vexillum*		3	2.15	2.45	2.70	2.12	2.46	2.76	4.99	6.03	7.03
Cnidaria	*Amphisbetia furcata*		1	1.07	1.42	1.82	1.46	1.80	2.17	1.74	2.55	3.52
Cnidaria	*Bougainvillia muscus*		3	1.22	1.56	1.96	1.62	2.00	2.33	2.23	3.13	4.11
Cnidaria	*Diadumene lineata*		2	1.22	1.57	1.97	2.00	2.32	2.67	2.74	3.65	4.73
Cnidaria	*Eutima japonica*		2	1.33	1.68	2.11	1.37	1.76	2.13	2.15	2.97	4.02
Cnidaria	*Halecium tenellum*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Hydrodendron gracilis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Metridium dianthus*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Obelia longissima*		2	1.33	1.66	2.04	1.87	2.23	2.59	2.77	3.71	4.83
Cnidaria	*Orthopyxis caliculata*		1	1.11	1.44	1.83	1.69	2.10	2.50	2.13	3.02	4.11
Cnidaria	*Orthopyxis platycarpa*	v	1	1.05	1.39	1.78	1.37	1.80	2.19	1.72	2.49	3.46
Cnidaria	*Plumularia setacea*		2	1.07	1.37	1.70	1.79	2.17	2.54	2.20	2.98	3.94
Cnidaria	*Pocillopora damicornis*		1	1.06	1.32	1.61	1.19	1.50	1.88	1.39	1.99	2.73
Cnidaria	*Sertularella mutsuensis*		1	1.05	1.37	1.78	1.24	1.62	2.06	1.53	2.24	3.15

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				North American Pacific Fijordland								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
Group	Species	Footnote	Invasion history score	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Crustacea	*Ampithoe lacertosa*		2	1.18	1.57	1.93	1.75	2.09	2.46	2.37	3.29	4.32
Crustacea	*Ampithoe valida*		3	1.55	1.93	2.30	1.71	2.04	2.33	3.05	3.94	4.94
Crustacea	*Balanus crenatus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus glandula*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus trigonus*		3	1.28	1.61	1.94	1.37	1.72	2.13	2.01	2.76	3.65
Crustacea	*Caprella cristibrachium*		1	1.11	1.46	1.83	1.31	1.66	2.13	1.60	2.43	3.34
Crustacea	*Caprella mutica*		3	1.66	1.98	2.34	2.16	2.44	2.67	3.80	4.81	5.91
Crustacea	*Caprella penantis*		3	1.32	1.64	2.00	1.71	2.05	2.42	2.50	3.34	4.40
Crustacea	*Chthamalus challengeri*		3	1.40	1.78	2.19	1.46	1.82	2.21	2.42	3.27	4.35
Crustacea	*Dactylopodamphiascopsis latifolius*		1	1.11	1.46	1.89	1.31	1.73	2.19	1.75	2.53	3.55
Crustacea	*Dynoides spinipodus*		1	1.11	1.47	1.89	1.31	1.71	2.19	1.71	2.52	3.56
Crustacea	*Gammaropsis japonica*		1	1.00	1.29	1.67	1.25	1.60	2.00	1.44	2.07	2.92
Crustacea	*Harpacticus compsonyx*	vi	1	1.11	1.46	1.83	1.37	1.73	2.19	1.67	2.52	3.56
Crustacea	*Harpacticus nicaeensis*		1	1.11	1.47	1.95	1.25	1.64	2.07	1.65	2.40	3.44
Crustacea	*Harpacticus septentrionalis*		1	1.11	1.47	1.89	1.44	1.82	2.25	1.83	2.67	3.65
Crustacea	*Harpacticus* sp. *-flexus* group	vii	1	1.11	1.46	1.83	1.37	1.76	2.19	1.75	2.57	3.56
Crustacea	*Hemigrapsus sanguineus*		3	2.07	2.40	2.74	1.79	2.14	2.50	3.98	5.13	6.21
Crustacea	*Heterolaophonte discophora*		1	1.11	1.46	1.83	1.49	1.86	2.25	1.90	2.72	3.67
Crustacea	*Ianiropsis serricaudis*		3	1.22	1.60	2.04	1.67	2.02	2.42	2.34	3.23	4.31
Crustacea	*Jassa marmorata*-complex		3	1.37	1.70	2.11	1.83	2.14	2.46	2.73	3.63	4.67
Crustacea	*Megabalanus rosa*		3	1.33	1.64	2.06	1.37	1.74	2.13	2.07	2.86	3.86
Crustacea	*Megabalanus zebra*		3	1.22	1.59	2.00	1.37	1.73	2.13	1.91	2.75	3.78
Crustacea	*Oedignathus inermis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Paralaophonte congenera*		1	1.11	1.46	1.83	1.37	1.74	2.19	1.78	2.55	3.46
Crustacea	*Paramphiascella fulvofasciata*		1	1.06	1.37	1.72	1.31	1.68	2.06	1.62	2.31	3.18
Crustacea	*Parastenhelia spinosa*		1	1.06	1.37	1.78	1.50	1.87	2.25	1.80	2.54	3.51
Crustacea	*Parathalestris intermedia*		1	1.11	1.46	1.89	1.56	1.90	2.31	1.91	2.78	3.86
Crustacea	*Pseudoctomeris sulcata*		2	1.22	1.57	2.06	1.19	1.61	2.06	1.71	2.51	3.65
Crustacea	*Sarsamphiascus minutus*		1	1.11	1.46	1.89	1.50	1.84	2.25	1.83	2.69	3.68
Crustacea	*Sarsamphiascus varians* group		1	1.11	1.46	1.89	1.25	1.63	2.06	1.60	2.37	3.32
Crustacea	*Semibalanus cariosus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Sphaerozius nitidus*		2	1.22	1.59	1.94	1.37	1.74	2.13	1.91	2.76	3.85
Crustacea	*Stenothoe crenulata*-complex		3	1.22	1.60	2.00	1.37	1.76	2.19	1.90	2.82	3.82
Crustacea	*Xestoleberis setouchiensis*		1	1.11	1.46	1.89	1.37	1.75	2.19	1.74	2.55	3.56
Crustacea	*Zeuxo normani*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Echinodermata	*Aphelasterias japonica*		1	1.17	1.55	1.95	1.43	1.83	2.19	1.98	2.83	3.79
Echinodermata	*Asterias amurensis*		3	1.92	2.29	2.63	2.08	2.43	2.75	4.40	5.55	6.63
Echinodermata	*Havelockia versicolor*		1	1.06	1.43	1.83	1.31	1.66	2.13	1.60	2.37	3.27
Echinodermata	*Patiria pectinifera*		1	1.11	1.42	1.78	1.37	1.75	2.13	1.74	2.48	3.38
Echinodermata	*Temnotrema sculptum*		1	1.17	1.52	1.94	1.19	1.59	2.00	1.67	2.42	3.34
Miscellaneous	*Cibicides lobatulus*	viii	1	1.00	1.29	1.67	1.75	2.07	2.38	1.97	2.67	3.54
Miscellaneous	*Endeis nodosa*		2	1.11	1.42	1.83	1.37	1.69	2.07	1.73	2.40	3.22
Miscellaneous	*Gromia oviformis*		1	1.00	1.30	1.67	1.75	2.07	2.44	1.96	2.69	3.62
Miscellaneous	*Halacarellus schefferi*		1	1.07	1.43	1.82	1.29	1.71	2.13	1.66	2.44	3.31
Miscellaneous	*Phascolosoma scolops*		3	1.33	1.69	2.06	1.44	1.80	2.19	2.11	3.01	4.02
Miscellaneous	*Telmatogeton japonicus*		3	1.28	1.59	1.95	1.50	1.79	2.13	2.06	2.84	3.83

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				North American Pacific Fjordland								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Mollusca	*Arca navicularis*		1	1.05	1.38	1.78	1.31	1.66	2.06	1.58	2.30	3.15
Mollusca	*Bankia bipennata*		1	1.11	1.46	1.89	1.37	1.79	2.25	1.80	2.62	3.67
Mollusca	*Bankia carinata*		1	1.11	1.48	1.89	1.44	1.83	2.19	1.87	2.71	3.67
Mollusca	*Barbatia virescens*	ix	1	1.05	1.38	1.73	1.31	1.68	2.06	1.58	2.32	3.23
Mollusca	*Crassostrea gigas*		3	1.85	2.17	2.49	1.78	2.13	2.42	3.67	4.61	5.64
Mollusca	*Crepidula onyx*		3	1.40	1.73	2.11	1.41	1.83	2.25	2.24	3.15	4.20
Mollusca	*Dendostrea folium*		2	1.17	1.53	1.89	1.44	1.80	2.19	1.96	2.75	3.76
Mollusca	*Dendronotus frondosus*		1	1.05	1.34	1.67	1.69	2.02	2.38	1.97	2.71	3.62
Mollusca	*Dolabella auricularia*		1	1.06	1.38	1.78	1.50	1.83	2.25	1.81	2.52	3.44
Mollusca	*Hermissenda crassicornis*		1	1.17	1.44	1.78	1.69	2.05	2.44	2.15	2.95	3.83
Mollusca	*Hiatella orientalis*	x	2	1.11	1.45	1.78	1.74	2.11	2.44	2.22	3.05	4.00
Mollusca	*Hyotissa chemnitzi*		1	1.11	1.46	1.89	1.25	1.67	2.13	1.66	2.45	3.44
Mollusca	*Hyotissa numisma*		1	1.11	1.48	1.89	1.31	1.68	2.13	1.67	2.49	3.54
Mollusca	*Isognomon legumen*		1	1.05	1.38	1.78	1.31	1.68	2.13	1.59	2.33	3.27
Mollusca	*Laevichlamys irregularis*		1	1.11	1.46	1.83	1.31	1.74	2.19	1.74	2.54	3.63
Mollusca	*Limaria hakodatensis*		1	1.11	1.45	1.83	1.50	1.84	2.25	1.87	2.68	3.67
Mollusca	*Lithophaga curta*		1	1.11	1.44	1.83	1.31	1.66	2.06	1.59	2.39	3.25
Mollusca	*Lyrodus takanoshimensis*		3	1.22	1.57	1.95	1.37	1.81	2.25	1.99	2.82	3.89
Mollusca	*Mitrella moleculina*		1	1.11	1.46	1.95	1.31	1.72	2.13	1.68	2.52	3.53
Mollusca	*Mizuhopecten yessoensis*	xi	1	1.11	1.45	1.83	1.62	2.00	2.38	2.11	2.92	3.92
Mollusca	*Modiolarca cuprea*	xii	1	1.11	1.46	1.89	1.25	1.68	2.13	1.67	2.45	3.52
Mollusca	*Modiolus nipponicus*		1	1.05	1.39	1.78	1.31	1.74	2.13	1.60	2.43	3.40
Mollusca	*Mopalia seta*		1	1.11	1.49	1.95	1.50	1.87	2.25	1.90	2.77	3.81
Mollusca	*Mytilisepta virgata*	xiii	1	1.10	1.44	1.84	1.31	1.70	2.13	1.66	2.44	3.37
Mollusca	*Mytilus coruscus*	xiv	1	1.05	1.37	1.78	1.56	1.95	2.31	1.91	2.68	3.56
Mollusca	*Mytilus galloprovincialis*		3	2.22	2.54	2.83	1.93	2.29	2.65	4.68	5.83	6.95
Mollusca	*Mytilus trossulus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Nipponacmea habei*		1	1.11	1.48	1.89	1.31	1.74	2.19	1.74	2.58	3.62
Mollusca	*Pascahinnites coruscans*		1	1.11	1.48	1.89	1.31	1.73	2.19	1.75	2.56	3.60
Mollusca	*Pinctada imbricata*		1	1.16	1.44	1.84	1.19	1.58	2.00	1.59	2.28	3.22
Mollusca	*Reishia bronni*	xv	1	1.21	1.56	1.89	1.31	1.64	2.06	1.81	2.55	3.55
Mollusca	*Scaeochlamys squamata*		1	1.11	1.48	1.89	1.31	1.75	2.19	1.74	2.59	3.64
Mollusca	*Sphenia coreanica*		3	1.22	1.58	2.00	1.37	1.76	2.13	1.96	2.78	3.79
Mollusca	*Spondylus cruentus*	xvi	1	1.11	1.46	1.83	1.25	1.69	2.13	1.67	2.47	3.52
Mollusca	*Teredo navalis*		3	1.37	1.67	2.07	1.75	2.10	2.42	2.59	3.51	4.59
Mollusca	*Teredothyra smithi*		1	1.05	1.41	1.78	1.25	1.63	2.06	1.53	2.30	3.24
Nemertea	*Oerstedia dorsalis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Nemertea	*Quasitetrastemma nigrifrons*	xvii	1	1.11	1.39	1.72	1.37	1.79	2.19	1.74	2.48	3.34

Now in JTMD list under name in column,
but searched as:

i	*Arabella semimaculata*
ii	*Arbocuspis bellula*
iv	*Membranipora serrilamella*
vi	*Harpacticus pacificus*
xii	*Musculus cupreus*
xi	*Patinopecten yessoensis*
xiii	*Septifer virgatus*
xvii	*Tetrastemma nigrifrons*

In JTMD list under name in column,
but referred to in marinespecies.org as:

iii	*Cauloramphus spiniferum* (Johnston 1832)
v	*Orthopyxis crenata* (Hartlaub 1901)
viii	*Lobatula lobatula* (Walker & Jacob 1798)
x	*Hiatella arctica* (Linnaeus 1767)
xiv	*Mytilus unguiculatus* (Valenciennes 1858)
xvi	*Spondylus squamosus* (Schreibers 1793)

Retained as name in column due to
similarities in data, but searched as:

iii	*Cauloramphus cryptoarmatus*
vii	*Harpacticus flexus*
xv	*Reishia clavigera*
ix	*Barbatia foliata*

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Oregon, Washington, Vancouver Coast and Shelf								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Annelida	*Amblyosyllis speciosa*		2	1.15	1.50	1.89	1.42	1.78	2.17	1.85	2.66	3.65
Annelida	*Arabella* sp. *semimaculata*-group	i	1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Eulalia quadrioculata*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Eulalia viridis*-complex		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Halosydna brevisetosa*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Harmothoe imbricata*		1	1.17	1.46	1.83	1.87	2.12	2.44	2.26	3.08	4.08
Annelida	*Hydroides ezoensis*		3	1.67	1.98	2.28	1.56	1.92	2.25	2.91	3.79	4.70
Annelida	*Nereis pelagica*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Perinereis nigropunctata*		1	1.15	1.45	1.89	1.37	1.76	2.17	1.79	2.57	3.57
Annelida	*Pygospio californica*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Spirobranchus polytrema*		2	1.28	1.65	2.06	1.62	2.01	2.38	2.33	3.31	4.49
Annelida	*Syllis elongata*-complex		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Syllis gracilis*-complex		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Syllis hyalina*-complex		1	1.07	1.42	1.81	1.50	1.87	2.29	1.86	2.67	3.73
Annelida	*Trypanosyllis zebra*		1	1.11	1.46	1.83	1.25	1.64	2.00	1.66	2.38	3.32
Bryozoa	*Aetea anguina*		2	1.18	1.47	1.86	1.87	2.20	2.54	2.37	3.23	4.17
Bryozoa	*Arbocuspis* n. sp.	ii	1	1.16	1.53	1.95	1.25	1.62	2.00	1.66	2.48	3.44
Bryozoa	*Biflustra grandicella*		3	1.48	1.86	2.23	1.58	1.99	2.38	2.71	3.69	4.73
Bryozoa	*Biflustra irregulata*		1	1.11	1.46	1.90	1.56	1.95	2.38	2.01	2.85	3.90
Bryozoa	*Callopora craticula*		1	1.00	1.29	1.67	1.50	1.82	2.19	1.67	2.36	3.21
Bryozoa	*Cauloramphus spinifer*	iii	1	1.11	1.46	1.83	1.37	1.79	2.25	1.81	2.61	3.66
Bryozoa	*Celleporella hyalina*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Celleporina porosissima*		1	1.10	1.46	1.89	1.56	1.97	2.38	2.01	2.88	3.90
Bryozoa	*Cryptosula pallasiana*		2	1.37	1.72	2.12	2.00	2.34	2.67	3.01	4.01	5.12
Bryozoa	*Escharella hozawai*		1	1.11	1.46	1.83	1.44	1.85	2.25	1.85	2.70	3.78
Bryozoa	*Exochella tricuspis*		1	1.11	1.51	1.95	1.44	1.83	2.25	1.83	2.77	3.87
Bryozoa	*Membranipora villosa*	iv	1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Microporella borealis*		1	1.11	1.47	1.89	1.50	1.92	2.32	1.94	2.84	3.90
Bryozoa	*Schizoporella japonica*		3	1.48	1.78	2.15	1.87	2.25	2.59	3.02	4.01	5.10
Bryozoa	*Smittoidea spinigera*		1	1.11	1.47	1.83	1.50	1.87	2.25	1.88	2.75	3.72
Bryozoa	*Tricellaria inopinata*		3	1.70	2.02	2.37	1.87	2.24	2.59	3.46	4.52	5.65
Bryozoa	*Tubulipora masakiensis*		1	1.11	1.46	1.83	1.50	1.88	2.31	1.92	2.76	3.79
Bryozoa	*Tubulipora pulchra*		1	1.11	1.45	1.89	1.56	1.92	2.38	1.94	2.80	3.85
Chordata	*Didemnum vexillum*		3	2.14	2.47	2.74	2.20	2.49	2.75	5.14	6.15	7.22
Cnidaria	*Amphisbetia furcata*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Bougainvillia muscus*		3	1.22	1.55	1.97	1.83	2.23	2.58	2.53	3.49	4.62
Cnidaria	*Diadumene lineata*		2	1.22	1.57	1.89	2.08	2.45	2.75	2.89	3.85	4.96
Cnidaria	*Eutima japonica*		2	1.33	1.68	2.11	1.56	1.92	2.31	2.33	3.22	4.25
Cnidaria	*Halecium tenellum*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Hydrodendron gracilis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Metridium dianthus*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Obelia longissima*		2	1.33	1.66	2.04	1.96	2.29	2.63	2.82	3.78	4.93
Cnidaria	*Orthopyxis caliculata*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Orthopyxis platycarpa*	v	1	1.05	1.38	1.78	1.50	1.86	2.25	1.74	2.57	3.52
Cnidaria	*Plumularia setacea*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Pocillopora damicornis*		1	1.06	1.32	1.67	1.19	1.51	1.88	1.39	2.00	2.74
Cnidaria	*Sertularella mutsuensis*		1	1.05	1.38	1.79	1.24	1.64	2.06	1.58	2.30	3.16

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Oregon, Washington, Vancouver Coast and Shelf								
				Adjusted IMPACT			**Adjusted LIKELIHOOD**			**Adjusted CMIST SCORE**		
				Lower confidence limit	**Mean**	**Upper confidence limit**	**Lower confidence limit**	**Mean**	**Upper confidence limit**	**Lower confidence limit**	**Mean**	**Upper confidence limit**
Group	**Species**	**Footnote**	**Invasion history score**									
Crustacea	*Ampithoe lacertosa*		2	1.22	1.57	2.00	1.83	2.19	2.54	2.52	3.43	4.50
Crustacea	*Ampithoe valida*		3	1.59	1.94	2.30	2.00	2.29	2.59	3.47	4.43	5.52
Crustacea	*Balanus crenatus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus glandula*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus trigonus*		3	1.28	1.60	2.00	1.50	1.80	2.13	2.14	2.89	3.78
Crustacea	*Caprella cristibrachium*		1	1.11	1.46	1.89	1.25	1.67	2.13	1.66	2.43	3.45
Crustacea	*Caprella mutica*		3	1.63	1.96	2.30	2.25	2.56	2.83	4.00	5.01	6.11
Crustacea	*Caprella penantis*		3	1.33	1.64	2.04	1.87	2.22	2.55	2.73	3.63	4.70
Crustacea	*Chthamalus challengeri*		3	1.40	1.78	2.19	1.71	2.07	2.42	2.77	3.72	4.73
Crustacea	*Dactylopodamphiascopsis latifolius*		1	1.11	1.46	1.83	1.31	1.72	2.19	1.71	2.52	3.55
Crustacea	*Dynoides spinipodus*		1	1.11	1.46	1.89	1.37	1.76	2.13	1.74	2.57	3.56
Crustacea	*Gammaropsis japonica*		1	1.00	1.29	1.67	1.49	1.81	2.19	1.72	2.34	3.22
Crustacea	*Harpacticus compsonyx*	vi	1	1.11	1.45	1.83	1.37	1.77	2.19	1.73	2.57	3.66
Crustacea	*Harpacticus nicaeensis*		1	1.11	1.46	1.83	1.25	1.68	2.13	1.67	2.46	3.47
Crustacea	*Harpacticus septentrionalis*		1	1.11	1.46	1.83	1.50	1.89	2.31	1.89	2.77	3.76
Crustacea	*Harpacticus* sp. *-flexus* group	vii	1	1.11	1.46	1.83	1.37	1.76	2.19	1.73	2.57	3.61
Crustacea	*Hemigrapsus sanguineus*		3	2.07	2.41	2.74	1.79	2.17	2.46	4.12	5.20	6.27
Crustacea	*Heterolaophonte discophora*		1	1.11	1.46	1.90	1.56	1.87	2.25	1.91	2.73	3.79
Crustacea	*Ianiropsis serricaudis*		3	1.26	1.60	1.96	1.91	2.27	2.63	2.66	3.62	4.79
Crustacea	*Jassa marmorata*-complex		3	1.33	1.71	2.11	1.95	2.25	2.59	2.85	3.82	4.91
Crustacea	*Megabalanus rosa*		3	1.33	1.65	2.06	1.56	1.89	2.25	2.25	3.13	4.10
Crustacea	*Megabalanus zebra*		3	1.22	1.59	2.00	1.44	1.78	2.19	1.99	2.83	3.88
Crustacea	*Oedignathus inermis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Paralaophonte congenera*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Paramphiascella fulvofasciata*		1	1.06	1.37	1.72	1.37	1.74	2.13	1.68	2.39	3.33
Crustacea	*Parastenhelia spinosa*		1	1.06	1.38	1.78	1.56	1.90	2.31	1.83	2.60	3.51
Crustacea	*Parathalestris intermedia*		1	1.11	1.45	1.83	1.44	1.80	2.19	1.76	2.61	3.65
Crustacea	*Pseudoctomeris sulcata*		2	1.22	1.57	2.00	1.19	1.61	2.00	1.74	2.52	3.60
Crustacea	*Sarsamphiascus minutus*		1	1.11	1.45	1.83	1.44	1.87	2.25	1.83	2.72	3.67
Crustacea	*Sarsamphiascus varians* group		1	1.11	1.46	1.83	1.25	1.62	2.06	1.59	2.37	3.34
Crustacea	*Semibalanus cariosus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Sphaerozius nitidus*		2	1.28	1.60	2.01	1.43	1.82	2.25	2.06	2.90	3.98
Crustacea	*Stenothoe crenulata*-complex		3	1.22	1.59	2.00	1.44	1.82	2.19	1.97	2.89	3.90
Crustacea	*Xestoleberis setouchiensis*		1	1.11	1.45	1.89	1.37	1.75	2.19	1.75	2.54	3.65
Crustacea	*Zeuxo normani*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Echinodermata	*Aphelasterias japonica*		1	1.17	1.54	1.95	1.50	1.83	2.19	2.02	2.82	3.86
Echinodermata	*Asterias amurensis*		3	1.96	2.32	2.63	2.12	2.47	2.84	4.47	5.72	6.92
Echinodermata	*Havelockia versicolor*		1	1.06	1.43	1.83	1.31	1.66	2.06	1.66	2.38	3.32
Echinodermata	*Patiria pectinifera*		1	1.11	1.43	1.83	1.37	1.77	2.19	1.81	2.53	3.35
Echinodermata	*Temnotrema sculptum*		1	1.17	1.52	1.94	1.19	1.59	2.00	1.67	2.43	3.33
Miscellaneous	*Cibicides lobatulus*	viii	1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Miscellaneous	*Endeis nodosa*		2	1.11	1.42	1.83	1.37	1.71	2.13	1.75	2.43	3.32
Miscellaneous	*Gromia oviformis*		1	1.00	1.29	1.67	1.75	2.07	2.44	1.94	2.66	3.60
Miscellaneous	*Halacarellus schefferi*		1	1.07	1.41	1.82	1.29	1.69	2.17	1.60	2.38	3.38
Miscellaneous	*Phascolosoma scolops*		3	1.33	1.70	2.11	1.50	1.84	2.19	2.23	3.11	4.10
Miscellaneous	*Telmatogeton japonicus*		3	1.33	1.60	1.95	1.50	1.81	2.19	2.12	2.89	3.79

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Oregon, Washington, Vancouver Coast and Shelf								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Mollusca	*Arca navicularis*		1	1.05	1.38	1.78	1.25	1.64	2.06	1.58	2.29	3.15
Mollusca	*Bankia bipennata*		1	1.11	1.47	1.89	1.37	1.81	2.25	1.82	2.67	3.67
Mollusca	*Bankia carinata*		1	1.11	1.48	1.89	1.44	1.83	2.25	1.87	2.71	3.79
Mollusca	*Barbatia virescens*	ix	1	1.05	1.38	1.78	1.31	1.74	2.13	1.72	2.41	3.35
Mollusca	*Crassostrea gigas*		3	1.81	2.17	2.49	1.95	2.28	2.59	3.99	4.93	5.93
Mollusca	*Crepidula onyx*		3	1.40	1.73	2.11	1.66	2.05	2.42	2.60	3.55	4.58
Mollusca	*Dendostrea folium*		2	1.17	1.53	1.89	1.50	1.89	2.31	2.00	2.88	3.89
Mollusca	*Dendronotus frondosus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Dolabella auricularia*		1	1.06	1.38	1.78	1.56	1.89	2.25	1.84	2.61	3.58
Mollusca	*Hermissenda crassicornis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Hiatella orientalis*	x	2	1.11	1.45	1.78	1.87	2.21	2.56	2.36	3.20	4.20
Mollusca	*Hyotissa chemnitzi*		1	1.11	1.46	1.89	1.31	1.72	2.19	1.71	2.53	3.56
Mollusca	*Hyotissa numisma*		1	1.11	1.49	1.89	1.31	1.67	2.13	1.67	2.49	3.45
Mollusca	*Isognomon legumen*		1	1.05	1.39	1.78	1.31	1.68	2.13	1.60	2.34	3.25
Mollusca	*Laevichlamys irregularis*		1	1.11	1.46	1.83	1.37	1.79	2.19	1.78	2.61	3.60
Mollusca	*Limaria hakodatensis*		1	1.11	1.47	1.83	1.50	1.84	2.25	1.87	2.71	3.67
Mollusca	*Lithophaga curta*		1	1.11	1.43	1.89	1.31	1.68	2.13	1.66	2.42	3.35
Mollusca	*Lyrodus takanoshimensis*		3	1.22	1.59	2.00	1.49	1.92	2.31	2.11	3.04	4.01
Mollusca	*Mitrella moleculina*		1	1.11	1.45	1.83	1.25	1.72	2.19	1.65	2.49	3.44
Mollusca	*Mizuhopecten yessoensis*	xi	1	1.11	1.45	1.89	1.62	2.00	2.38	2.12	2.92	3.92
Mollusca	*Modiolarca cuprea*	xii	1	1.11	1.47	1.89	1.25	1.68	2.13	1.67	2.46	3.44
Mollusca	*Modiolus nipponicus*		1	1.05	1.38	1.78	1.31	1.75	2.13	1.71	2.42	3.35
Mollusca	*Mopalia seta*		1	1.11	1.49	1.89	1.50	1.87	2.25	1.90	2.78	3.85
Mollusca	*Mytilisepta virgata*	xiii	1	1.10	1.44	1.84	1.31	1.71	2.13	1.67	2.46	3.36
Mollusca	*Mytilus coruscus*	xiv	1	1.11	1.37	1.73	1.75	2.08	2.44	2.08	2.84	3.75
Mollusca	*Mytilus galloprovincialis*		3	2.22	2.55	2.83	2.30	2.60	2.89	5.54	6.62	7.64
Mollusca	*Mytilus trossulus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Nipponacmea habei*		1	1.11	1.49	1.89	1.37	1.79	2.25	1.81	2.67	3.76
Mollusca	*Pascahinnites coruscans*		1	1.11	1.48	1.89	1.31	1.72	2.19	1.75	2.55	3.66
Mollusca	*Pinctada imbricata*		1	1.11	1.44	1.84	1.31	1.63	2.06	1.64	2.35	3.33
Mollusca	*Reishia bronni*	xv	1	1.21	1.56	1.95	1.37	1.70	2.13	1.89	2.65	3.65
Mollusca	*Scaeochlamys squamata*		1	1.11	1.49	1.89	1.37	1.81	2.25	1.83	2.69	3.67
Mollusca	*Sphenia coreanica*		3	1.28	1.59	1.94	1.50	1.92	2.31	2.14	3.05	4.01
Mollusca	*Spondylus cruentus*	xvi	1	1.11	1.46	1.89	1.25	1.67	2.13	1.67	2.45	3.44
Mollusca	*Teredo navalis*		3	1.36	1.67	2.00	1.87	2.22	2.55	2.86	3.70	4.73
Mollusca	*Teredothyra smithi*		1	1.05	1.41	1.84	1.25	1.63	2.06	1.58	2.30	3.24
Nemertea	*Oerstedia dorsalis*		1	1.17	1.49	1.89	1.62	1.99	2.38	2.13	2.96	3.91
Nemertea	*Quasitetrastemma nigrifrons*	xvii	1	Native	Native	Native	Native	Native	Native	Native	Native	Native

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Now in JTMD list under name in column, but searched as:

i	*Arabella semimaculata*
ii	*Arbocuspis bellula*
iv	*Membranipora serrilamella*
vi	*Harpacticus pacificus*
xii	*Musculus cupreus*
xi	*Patinopecten yessoensis*
xiii	*Septifer virgatus*
xvii	*Tetrastemma nigrifrons*

In JTMD list under name in column, but referred to in marinespecies.org as:

iii	*Cauloramphus spiniferum* (Johnston 1832)
v	*Orthopyxis crenata* (Hartlaub 1901)
viii	*Lobatula lobatula* (Walker & Jacob 1798)
x	*Hiatella arctica* (Linnaeus 1767)
xiv	*Mytilus unguiculatus* (Valenciennes 1858)
xvi	*Spondylus squamosus* (Schreibers 1793)

Retained as name in column due to similarities in data, but searched as:

iii	*Cauloramphus cryptoarmatus*
vii	*Harpacticus flexus*
xv	*Reishia clavigera*
ix	*Barbatia foliata*

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Northern California								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Annelida	*Amblyosyllis speciosa*		2	1.15	1.49	1.89	1.29	1.68	2.08	1.68	2.51	3.49
Annelida	*Arabella* sp. *semimaculata*-group	i	1	1.11	1.46	1.85	1.71	2.12	2.54	2.17	3.10	4.23
Annelida	*Eulalia quadrioculata*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Eulalia viridis*-complex		1	1.11	1.42	1.84	1.44	1.83	2.19	1.81	2.59	3.55
Annelida	*Halosydna brevisetosa*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Harmothoe imbricata*		1	1.17	1.46	1.83	1.87	2.12	2.50	2.32	3.09	4.08
Annelida	*Hydroides ezoensis*		3	1.67	1.98	2.33	1.75	2.09	2.44	3.12	4.14	5.13
Annelida	*Nereis pelagica*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Perinereis nigropunctata*		1	1.14	1.46	1.89	1.37	1.81	2.21	1.83	2.64	3.70
Annelida	*Pygospio californica*		1	1.11	1.47	1.89	1.67	2.08	2.50	2.17	3.06	4.20
Annelida	*Spirobranchus polytrema*		2	1.28	1.66	2.06	1.68	2.11	2.50	2.46	3.48	4.67
Annelida	*Syllis elongata*-complex		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Syllis gracilis*-complex		1	1.11	1.49	1.89	1.31	1.68	2.13	1.66	2.50	3.45
Annelida	*Syllis hyalina*-complex		1	1.07	1.41	1.78	1.54	1.88	2.29	1.86	2.66	3.67
Annelida	*Trypanosyllis zebra*		1	1.11	1.46	1.95	1.37	1.70	2.06	1.66	2.49	3.51
Bryozoa	*Aetea anguina*		2	1.18	1.47	1.89	1.92	2.26	2.59	2.43	3.31	4.38
Bryozoa	*Arbocuspis* n. sp.	ii	1	1.16	1.53	2.00	1.31	1.70	2.13	1.79	2.60	3.63
Bryozoa	*Biflustra grandicella*		3	1.48	1.86	2.23	1.67	2.07	2.46	2.78	3.84	4.99
Bryozoa	*Biflustra irregulata*		1	1.11	1.46	1.89	1.56	1.96	2.38	2.01	2.87	3.90
Bryozoa	*Callopora craticula*		1	1.00	1.29	1.67	1.37	1.72	2.06	1.58	2.21	3.00
Bryozoa	*Cauloramphus spinifer*	iii	1	1.11	1.47	1.89	1.37	1.78	2.19	1.74	2.61	3.63
Bryozoa	*Celleporella hyalina*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Celleporina porosissima*		1	1.17	1.46	1.89	1.56	1.97	2.38	1.98	2.89	3.90
Bryozoa	*Cryptosula pallasiana*		2	1.37	1.71	2.08	1.99	2.40	2.71	3.12	4.11	5.11
Bryozoa	*Escharella hozawai*		1	1.11	1.45	1.83	1.44	1.86	2.25	1.85	2.70	3.77
Bryozoa	*Exochella tricuspis*		1	1.11	1.51	1.95	1.44	1.84	2.25	1.94	2.77	3.78
Bryozoa	*Membranipora villosa*	iv	1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Microporella borealis*		1	1.11	1.49	1.89	1.50	1.91	2.32	1.99	2.85	3.99
Bryozoa	*Schizoporella japonica*		3	1.48	1.78	2.11	1.92	2.31	2.67	3.09	4.10	5.19
Bryozoa	*Smittoidea spinigera*		1	1.11	1.46	1.83	1.50	1.88	2.25	1.84	2.74	3.87
Bryozoa	*Tricellaria inopinata*		3	1.70	2.02	2.37	1.96	2.35	2.71	3.69	4.76	6.00
Bryozoa	*Tubulipora masakiensis*		1	1.11	1.46	1.83	1.50	1.89	2.31	1.92	2.77	3.79
Bryozoa	*Tubulipora pulchra*		1	1.11	1.46	1.83	1.56	1.92	2.38	1.92	2.80	3.85
Chordata	*Didemnum vexillum*		3	2.15	2.45	2.75	2.32	2.64	2.88	5.46	6.47	7.45
Cnidaria	*Amphisbetia furcata*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Bougainvillia muscus*		3	1.19	1.55	1.89	1.96	2.33	2.67	2.64	3.63	4.78
Cnidaria	*Diadumene lineata*		2	1.22	1.57	1.93	2.20	2.54	2.80	3.05	3.97	5.11
Cnidaria	*Eutima japonica*		2	1.33	1.67	2.11	1.56	1.92	2.32	2.33	3.21	4.25
Cnidaria	*Halecium tenellum*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Hydrodendron gracilis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Metridium dianthus*		2	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Obelia longissima*		2	1.30	1.66	2.07	2.00	2.34	2.67	2.90	3.86	5.01
Cnidaria	*Orthopyxis caliculata*		1	1.11	1.44	1.83	1.62	2.02	2.44	2.04	2.91	3.96
Cnidaria	*Orthopyxis platycarpa*	v	1	1.05	1.38	1.78	1.37	1.73	2.13	1.66	2.40	3.34
Cnidaria	*Plumularia setacea*		2	1.07	1.37	1.74	1.87	2.23	2.59	2.25	3.08	4.07
Cnidaria	*Pocillopora damicornis*		1	1.06	1.31	1.67	1.31	1.62	2.00	1.53	2.15	2.95
Cnidaria	*Sertularella mutsuensis*		1	1.05	1.37	1.73	1.24	1.62	2.06	1.53	2.24	3.16

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Northern California								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Crustacea	*Ampithoe lacertosa*		2	1.22	1.56	1.96	1.87	2.26	2.59	2.61	3.52	4.51
Crustacea	*Ampithoe valida*		3	1.59	1.93	2.26	2.00	2.36	2.67	3.53	4.57	5.65
Crustacea	*Balanus crenatus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus glandula*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Balanus trigonus*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Caprella cristibrachium*		1	1.11	1.46	1.83	1.37	1.72	2.19	1.66	2.52	3.57
Crustacea	*Caprella mutica*		3	1.59	1.96	2.26	2.33	2.59	2.84	4.05	5.08	6.12
Crustacea	*Caprella penantis*		3	1.37	1.64	2.08	2.00	2.33	2.63	2.90	3.80	4.89
Crustacea	*Chthamalus challengeri*		3	1.44	1.78	2.19	1.83	2.20	2.55	2.90	3.95	5.05
Crustacea	*Dactylopodamphiascopsis latifolius*		1	1.11	1.46	1.83	1.44	1.78	2.19	1.74	2.60	3.56
Crustacea	*Dynoides spinipodus*		1	1.11	1.46	1.83	1.44	1.82	2.25	1.81	2.66	3.75
Crustacea	*Gammaropsis japonica*		1	1.00	1.29	1.67	1.49	1.81	2.19	1.67	2.35	3.21
Crustacea	*Harpacticus compsonyx*	vi	1	1.11	1.47	1.89	1.31	1.74	2.13	1.80	2.55	3.54
Crustacea	*Harpacticus nicaeensis*		1	1.11	1.45	1.83	1.37	1.71	2.13	1.68	2.49	3.46
Crustacea	*Harpacticus septentrionalis*		1	1.11	1.46	1.83	1.50	1.86	2.25	1.88	2.72	3.72
Crustacea	*Harpacticus* sp. *-flexus* group	vii	1	1.11	1.45	1.89	1.37	1.76	2.19	1.75	2.56	3.55
Crustacea	*Hemigrapsus sanguineus*		3	2.07	2.40	2.71	1.95	2.29	2.63	4.36	5.48	6.49
Crustacea	*Heterolaophonte discophora*		1	1.11	1.46	1.89	1.50	1.87	2.25	1.89	2.74	3.80
Crustacea	*Ianiropsis serricaudis*		3	1.26	1.61	2.04	2.04	2.37	2.67	2.85	3.80	4.97
Crustacea	*Jassa marmorata*-complex		3	1.33	1.71	2.11	2.00	2.32	2.63	2.94	3.92	5.09
Crustacea	*Megabalanus rosa*		3	1.33	1.65	2.06	1.62	1.96	2.31	2.39	3.23	4.26
Crustacea	*Megabalanus zebra*		3	1.22	1.59	2.00	1.56	1.94	2.31	2.16	3.07	4.14
Crustacea	*Oedignathus inermis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Paralaophonte congenera*		1	1.11	1.46	1.83	1.31	1.70	2.13	1.67	2.49	3.47
Crustacea	*Paramphiascella fulvofasciata*		1	1.06	1.37	1.78	1.31	1.73	2.13	1.65	2.37	3.32
Crustacea	*Parastenhelia spinosa*		1	1.06	1.37	1.78	1.56	1.87	2.19	1.81	2.55	3.44
Crustacea	*Parathalestris intermedia*		1	1.11	1.46	1.89	1.37	1.74	2.13	1.74	2.55	3.56
Crustacea	*Pseudoctomeris sulcata*		2	1.22	1.57	1.95	1.25	1.65	2.13	1.73	2.59	3.66
Crustacea	*Sarsamphiascus minutus*		1	1.11	1.46	1.89	1.50	1.91	2.31	1.89	2.79	3.87
Crustacea	*Sarsamphiascus varians* group		1	1.11	1.46	1.89	1.25	1.62	2.06	1.58	2.37	3.32
Crustacea	*Semibalanus cariosus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Sphaerozius nitidus*		2	1.28	1.59	1.94	1.44	1.90	2.31	2.14	3.01	4.01
Crustacea	*Stenothoe crenulata*-complex		3	1.22	1.60	2.00	1.50	1.92	2.31	2.14	3.07	4.13
Crustacea	*Xestoleberis setouchiensis*		1	1.11	1.46	1.83	1.37	1.75	2.13	1.74	2.56	3.56
Crustacea	*Zeuxo normani*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Echinodermata	*Aphelasterias japonica*		1	1.17	1.55	1.95	1.50	1.84	2.25	2.05	2.84	3.89
Echinodermata	*Asterias amurensis*		3	1.96	2.32	2.63	2.00	2.41	2.71	4.47	5.57	6.71
Echinodermata	*Havelockia versicolor*		1	1.11	1.43	1.83	1.31	1.66	2.13	1.65	2.37	3.35
Echinodermata	*Patiria pectinifera*		1	1.11	1.42	1.83	1.50	1.84	2.25	1.90	2.60	3.44
Echinodermata	*Temnotrema sculptum*		1	1.17	1.51	1.94	1.31	1.68	2.06	1.75	2.55	3.60
Miscellaneous	*Cibicides lobatulus*	viii	1	1.00	1.29	1.67	1.81	2.17	2.44	2.06	2.80	3.72
Miscellaneous	*Endeis nodosa*		2	1.11	1.42	1.83	1.50	1.91	2.31	1.94	2.71	3.62
Miscellaneous	*Gromia oviformis*		1	1.00	1.29	1.61	1.81	2.17	2.50	2.04	2.80	3.75
Miscellaneous	*Halacarellus schefferi*		1	1.07	1.41	1.82	1.29	1.67	2.13	1.61	2.35	3.32
Miscellaneous	*Phascolosoma scolops*		3	1.33	1.70	2.11	1.62	1.98	2.31	2.42	3.35	4.38
Miscellaneous	*Telmatogeton japonicus*		3	1.28	1.59	1.95	1.69	1.98	2.31	2.35	3.14	4.01

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

Group	Species	Footnote	Invasion history score	Northern California								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Mollusca	*Arca navicularis*		1	1.05	1.38	1.73	1.25	1.66	2.06	1.51	2.30	3.14
Mollusca	*Bankia bipennata*		1	1.11	1.47	1.89	1.44	1.84	2.25	1.83	2.71	3.77
Mollusca	*Bankia carinata*		1	1.11	1.47	1.89	1.50	1.86	2.25	1.87	2.73	3.78
Mollusca	*Barbatia virescens*	ix	1	1.05	1.38	1.78	1.44	1.82	2.25	1.72	2.52	3.52
Mollusca	*Crassostrea gigas*		3	1.85	2.17	2.48	2.03	2.33	2.63	4.08	5.05	6.02
Mollusca	*Crepidula onyx*		3	1.40	1.73	2.12	1.66	2.06	2.46	2.60	3.56	4.65
Mollusca	*Dendostrea folium*		2	1.16	1.53	1.89	1.56	1.89	2.31	2.11	2.89	3.90
Mollusca	*Dendronotus frondosus*		1	1.05	1.33	1.73	1.50	1.85	2.25	1.74	2.47	3.40
Mollusca	*Dolabella auricularia*		1	1.06	1.38	1.78	1.56	1.90	2.32	1.84	2.62	3.55
Mollusca	*Hermissenda crassicornis*		1	1.17	1.43	1.78	1.81	2.12	2.45	2.25	3.02	3.89
Mollusca	*Hiatella orientalis*	x	2	1.11	1.44	1.78	1.87	2.25	2.57	2.42	3.23	4.23
Mollusca	*Hyotissa chemnitzi*		1	1.11	1.46	1.89	1.37	1.76	2.13	1.76	2.56	3.44
Mollusca	*Hyotissa numisma*		1	1.11	1.49	1.89	1.31	1.72	2.19	1.73	2.57	3.69
Mollusca	*Isognomon legumen*		1	1.05	1.38	1.78	1.31	1.68	2.13	1.55	2.33	3.26
Mollusca	*Laevichlamys irregularis*		1	1.11	1.46	1.83	1.44	1.84	2.25	1.90	2.68	3.66
Mollusca	*Limaria hakodatensis*		1	1.11	1.46	1.89	1.50	1.88	2.25	1.94	2.76	3.77
Mollusca	*Lithophaga curta*		1	1.11	1.43	1.83	1.37	1.72	2.13	1.65	2.47	3.36
Mollusca	*Lyrodus takanoshimensis*		3	1.22	1.57	1.95	1.50	1.88	2.31	2.08	2.95	4.01
Mollusca	*Mitrella moleculina*		1	1.11	1.46	1.89	1.31	1.72	2.13	1.67	2.51	3.53
Mollusca	*Mizuhopecten yessoensis*	xi	1	1.11	1.45	1.83	1.62	1.96	2.38	2.01	2.86	3.90
Mollusca	*Modiolarca cuprea*	xii	1	1.11	1.46	1.83	1.37	1.77	2.19	1.74	2.59	3.56
Mollusca	*Modiolus nipponicus*		1	1.05	1.38	1.78	1.31	1.74	2.13	1.65	2.41	3.35
Mollusca	*Mopalia seta*		1	1.11	1.48	1.89	1.50	1.87	2.19	1.96	2.76	3.76
Mollusca	*Mytilisepta virgata*	xiii	1	1.10	1.44	1.84	1.31	1.70	2.13	1.68	2.45	3.43
Mollusca	*Mytilus coruscus*	xiv	1	1.11	1.36	1.73	1.75	2.17	2.50	2.15	2.96	3.97
Mollusca	*Mytilus galloprovincialis*		3	2.22	2.54	2.83	2.37	2.69	2.97	5.71	6.86	7.85
Mollusca	*Mytilus trossulus*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Nipponacmea habei*		1	1.11	1.48	1.89	1.37	1.79	2.25	1.81	2.66	3.76
Mollusca	*Pascahinnites coruscans*		1	1.11	1.48	1.89	1.31	1.73	2.13	1.75	2.56	3.54
Mollusca	*Pinctada imbricata*		1	1.05	1.43	1.78	1.31	1.66	2.13	1.60	2.38	3.33
Mollusca	*Reishia bronni*	xv	1	1.17	1.56	1.89	1.37	1.78	2.19	1.99	2.76	3.67
Mollusca	*Scaeochlamys squamata*		1	1.11	1.49	1.89	1.44	1.86	2.31	1.91	2.76	3.79
Mollusca	*Sphenia coreanica*		3	1.28	1.59	2.00	1.75	2.11	2.44	2.44	3.35	4.47
Mollusca	*Spondylus cruentus*	xvi	1	1.11	1.46	1.83	1.25	1.68	2.13	1.67	2.46	3.53
Mollusca	*Teredo navalis*		3	1.37	1.67	2.04	1.99	2.35	2.67	3.03	3.92	5.05
Mollusca	*Teredothyra smithi*		1	1.05	1.41	1.78	1.25	1.62	2.06	1.58	2.29	3.31
Nemertea	*Oerstedia dorsalis*		1	1.17	1.50	1.89	1.56	1.95	2.31	2.10	2.91	4.00
Nemertea	*Quasitetrastemma nigrifrons*	xvii	1	1.11	1.40	1.78	1.50	1.89	2.25	1.85	2.63	3.56

Now in JTMD list under name in column, but searched as:

i *Arabella semimaculata*
ii *Arbocuspis bellula*
iv *Membranipora serrilamella*
vi *Harpacticus pacificus*
xii *Musculus cupreus*
xi *Patinopecten yessoensis*
xiii *Septifer virgatus*
xvii *Tetrastemma nigrifrons*

In JTMD list under name in column, but referred to in marinespecies.org as:

iii *Cauloramphus spiniferum* (Johnston 1832)
v *Orthopyxis crenata* (Hartlaub 1901)
viii *Lobatula lobatula* (Walker & Jacob 1798)
x *Hiatella arctica* (Linnaeus 1767)
xiv *Mytilus unguiculatus* (Valenciennes 1858)
xvi *Spondylus squamosus* (Schreibers 1793)

Retained as name in column due to similarities in data, but searched as:

iii *Cauloramphus cryptoarmatus*
vii *Harpacticus flexus*
xv *Reishia clavigera*
ix *Barbatia foliata*

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Hawaii								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Annelida	*Amblyosyllis speciosa*		2	1.11	1.47	1.89	1.25	1.62	2.00	1.65	2.39	3.33
Annelida	*Arabella* sp. *semimaculata*-group	i	1	1.11	1.46	1.85	1.50	1.87	2.29	1.90	2.74	3.80
Annelida	*Eulalia quadrioculata*		1	1.11	1.48	1.89	1.41	1.78	2.17	1.77	2.63	3.62
Annelida	*Eulalia viridis*-complex		1	1.11	1.42	1.78	1.37	1.77	2.19	1.78	2.50	3.33
Annelida	*Halosydna brevisetosa*		1	1.11	1.44	1.82	1.42	1.78	2.13	1.81	2.56	3.48
Annelida	*Harmothoe imbricata*		1	1.11	1.43	1.78	1.55	1.87	2.19	1.95	2.67	3.63
Annelida	*Hydroides ezoensis*		3	1.61	1.95	2.28	1.81	2.13	2.44	3.22	4.14	5.01
Annelida	*Nereis pelagica*		2	1.39	1.69	2.06	1.44	1.84	2.19	2.26	3.09	4.01
Annelida	*Perinereis nigropunctata*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Annelida	*Pygospio californica*		1	1.11	1.48	1.89	1.46	1.84	2.21	1.90	2.72	3.78
Annelida	*Spirobranchus polytrema*		2	1.28	1.65	2.06	1.69	2.09	2.44	2.47	3.44	4.59
Annelida	*Syllis elongata*-complex		1	1.11	1.48	1.89	1.50	1.84	2.25	1.90	2.73	3.77
Annelida	*Syllis gracilis*-complex		1	1.11	1.48	1.89	1.44	1.84	2.25	1.89	2.73	3.78
Annelida	*Syllis hyalina*-complex		1	1.07	1.41	1.85	1.46	1.88	2.29	1.82	2.67	3.69
Annelida	*Trypanosyllis zebra*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Bryozoa	*Aetea anguina*		2	1.18	1.46	1.86	1.79	2.15	2.46	2.32	3.15	4.16
Bryozoa	*Arbocuspis* n. sp.	ii	1	1.16	1.53	1.95	1.37	1.75	2.19	1.89	2.68	3.75
Bryozoa	*Biflustra grandicella*		3	1.48	1.87	2.27	1.62	2.00	2.42	2.71	3.73	4.84
Bryozoa	*Biflustra irregulata*		1	1.11	1.46	1.83	1.56	1.96	2.38	2.05	2.86	3.90
Bryozoa	*Callopora craticula*		1	1.00	1.29	1.67	1.37	1.67	2.06	1.56	2.16	2.98
Bryozoa	*Cauloramphus spinifer*	iii	1	1.11	1.47	1.89	1.25	1.65	2.06	1.67	2.42	3.33
Bryozoa	*Celleporella hyalina*		2	1.38	1.69	2.06	1.50	1.84	2.19	2.25	3.10	4.10
Bryozoa	*Celleporina porosissima*		1	1.17	1.46	1.89	1.44	1.78	2.19	1.83	2.61	3.66
Bryozoa	*Cryptosula pallasiana*		2	1.37	1.72	2.07	1.62	1.96	2.29	2.44	3.36	4.30
Bryozoa	*Escharella hozawai*		1	1.11	1.46	1.83	1.31	1.73	2.13	1.74	2.52	3.53
Bryozoa	*Exochella tricuspis*		1	1.11	1.52	1.95	1.37	1.78	2.19	1.90	2.71	3.67
Bryozoa	*Membranipora villosa*	iv	1	1.17	1.44	1.78	1.44	1.75	2.13	1.82	2.51	3.42
Bryozoa	*Microporella borealis*		1	1.11	1.48	1.89	1.37	1.79	2.25	1.83	2.65	3.65
Bryozoa	*Schizoporella japonica*		3	1.44	1.76	2.11	1.54	1.92	2.30	2.51	3.36	4.41
Bryozoa	*Smittoidea spinigera*		1	1.11	1.46	1.83	1.50	1.87	2.32	1.90	2.73	3.78
Bryozoa	*Tricellaria inopinata*		3	1.66	2.01	2.37	1.67	2.01	2.38	3.09	4.05	5.02
Bryozoa	*Tubulipora masakiensis*		1	1.11	1.46	1.89	1.31	1.72	2.13	1.67	2.51	3.53
Bryozoa	*Tubulipora pulchra*		1	1.11	1.45	1.89	1.50	1.90	2.31	1.94	2.76	3.83
Chordata	*Didemnum vexillum*		3	2.11	2.42	2.70	1.91	2.24	2.59	4.40	5.43	6.48
Cnidaria	*Amphisbetia furcata*		1	1.07	1.41	1.82	1.37	1.76	2.17	1.74	2.48	3.41
Cnidaria	*Bougainvillia muscus*		3	1.22	1.56	1.96	2.00	2.35	2.67	2.69	3.66	4.80
Cnidaria	*Diadumene lineata*		2	1.26	1.57	2.00	2.12	2.45	2.75	2.85	3.85	4.97
Cnidaria	*Eutima japonica*		2	1.33	1.69	2.06	1.62	1.97	2.32	2.48	3.33	4.37
Cnidaria	*Halecium tenellum*		1	1.05	1.33	1.67	1.50	1.81	2.19	1.74	2.41	3.28
Cnidaria	*Hydrodendron gracilis*		1	1.11	1.45	1.85	1.37	1.77	2.21	1.77	2.57	3.55
Cnidaria	*Metridium dianthus*		2	1.39	1.73	2.06	1.50	1.82	2.19	2.33	3.14	4.12
Cnidaria	*Obelia longissima*		2	1.30	1.66	2.00	1.58	1.97	2.29	2.39	3.26	4.24
Cnidaria	*Orthopyxis caliculata*		1	1.11	1.44	1.83	1.44	1.82	2.19	1.80	2.63	3.68
Cnidaria	*Orthopyxis platycarpa*	v	1	1.05	1.38	1.78	1.36	1.75	2.13	1.72	2.43	3.35
Cnidaria	*Plumularia setacea*		2	1.07	1.37	1.71	1.66	2.03	2.38	2.04	2.79	3.74
Cnidaria	*Pocillopora damicornis*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Cnidaria	*Sertularella mutsuensis*		1	1.05	1.37	1.73	1.19	1.55	2.00	1.44	2.14	3.03

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Hawaii								
				Adjusted IMPACT			Adjusted LIKELIHOOD			Adjusted CMIST SCORE		
				Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit	Lower confidence limit	Mean	Upper confidence limit
Group	**Species**	**Footnote**	**Invasion history score**									
Crustacea	*Ampithoe lacertosa*		2	1.18	1.57	2.00	1.42	1.75	2.17	1.92	2.74	3.64
Crustacea	*Ampithoe valida*		3	1.59	1.92	2.26	1.46	1.86	2.21	2.68	3.57	4.61
Crustacea	*Balanus crenatus*		1	1.11	1.38	1.78	1.44	1.82	2.19	1.76	2.50	3.43
Crustacea	*Balanus glandula*		3	1.62	1.91	2.23	1.54	1.89	2.25	2.81	3.64	4.57
Crustacea	*Balanus trigonus*		3	Native	Native	Native	Native	Native	Native	Native	Native	Native
Crustacea	*Caprella cristibrachium*		1	1.11	1.46	1.83	1.25	1.66	2.13	1.66	2.42	3.44
Crustacea	*Caprella mutica*		3	1.63	1.97	2.34	1.70	2.05	2.38	3.12	4.02	5.06
Crustacea	*Caprella penantis*		3	1.37	1.64	1.96	1.87	2.29	2.59	2.82	3.76	4.84
Crustacea	*Chthamalus challengeri*		3	1.44	1.76	2.15	1.71	2.05	2.42	2.68	3.64	4.67
Crustacea	*Dactylopodamphiascopsis latifolius*		1	1.11	1.46	1.90	1.25	1.68	2.13	1.65	2.46	3.45
Crustacea	*Dynoides spinipodus*		1	1.11	1.45	1.83	1.37	1.76	2.19	1.71	2.56	3.60
Crustacea	*Gammaropsis japonica*		1	1.00	1.29	1.67	1.31	1.68	2.06	1.51	2.18	3.02
Crustacea	*Harpacticus compsonyx*	vi	1	1.11	1.45	1.83	1.31	1.70	2.06	1.67	2.47	3.36
Crustacea	*Harpacticus nicaeensis*		1	1.11	1.46	1.83	1.37	1.75	2.13	1.78	2.56	3.54
Crustacea	*Harpacticus septentrionalis*		1	1.11	1.47	1.89	1.31	1.68	2.13	1.68	2.48	3.46
Crustacea	*Harpacticus* sp. *-flexus* group	vii	1	1.11	1.46	1.89	1.31	1.65	2.06	1.64	2.41	3.40
Crustacea	*Hemigrapsus sanguineus*		3	2.04	2.36	2.67	1.92	2.25	2.54	4.19	5.29	6.38
Crustacea	*Heterolaophonte discophora*		1	1.11	1.46	1.89	1.31	1.68	2.06	1.73	2.46	3.45
Crustacea	*Ianiropsis serricaudis*		3	1.26	1.60	2.00	1.58	1.95	2.33	2.19	3.12	4.22
Crustacea	*Jassa marmorata*-complex		3	1.37	1.71	2.11	1.50	1.90	2.29	2.34	3.22	4.31
Crustacea	*Megabalanus rosa*		3	1.33	1.66	2.06	1.75	2.08	2.44	2.59	3.45	4.38
Crustacea	*Megabalanus zebra*		3	1.22	1.59	2.00	1.62	2.06	2.44	2.31	3.29	4.37
Crustacea	*Oedignathus inermis*		1	1.00	1.29	1.67	1.37	1.68	2.06	1.53	2.17	2.92
Crustacea	*Paralaophonte congenera*		1	1.11	1.46	1.83	1.25	1.64	2.07	1.65	2.39	3.35
Crustacea	*Paramphiascella fulvofasciata*		1	1.06	1.37	1.72	1.25	1.59	2.00	1.46	2.18	3.01
Crustacea	*Parastenhelia spinosa*		1	1.06	1.37	1.72	1.31	1.68	2.06	1.57	2.30	3.22
Crustacea	*Parathalestris intermedia*		1	1.11	1.46	1.89	1.31	1.70	2.13	1.69	2.48	3.57
Crustacea	*Pseudoctomeris sulcata*		2	1.22	1.57	2.00	1.37	1.75	2.19	1.91	2.76	3.79
Crustacea	*Sarsamphiascus minutus*		1	1.11	1.46	1.90	1.37	1.72	2.19	1.70	2.52	3.61
Crustacea	*Sarsamphiascus varians* group		1	1.11	1.46	1.83	1.56	1.91	2.25	1.94	2.79	3.84
Crustacea	*Semibalanus cariosus*		1	1.00	1.29	1.61	1.37	1.70	2.13	1.53	2.19	2.99
Crustacea	*Sphaerozius nitidus*		2	1.22	1.60	2.06	1.56	1.96	2.44	2.17	3.12	4.22
Crustacea	*Stenothoe crenulata*-complex		3	1.22	1.59	2.00	1.62	2.02	2.44	2.26	3.22	4.37
Crustacea	*Xestoleberis setouchiensis*		1	1.11	1.46	1.83	1.37	1.80	2.19	1.80	2.63	3.56
Crustacea	*Zeuxo normani*		1	1.11	1.50	1.95	1.37	1.74	2.19	1.81	2.61	3.66
Echinodermata	*Aphelasterias japonica*		1	1.11	1.53	1.89	1.50	1.84	2.25	1.93	2.81	3.78
Echinodermata	*Asterias amurensis*		3	1.89	2.21	2.56	1.83	2.19	2.54	3.77	4.83	5.92
Echinodermata	*Havelockia versicolor*		1	1.11	1.50	1.89	1.50	1.93	2.38	2.03	2.91	4.00
Echinodermata	*Patiria pectinifera*		1	1.06	1.36	1.78	1.56	1.96	2.38	1.87	2.65	3.55
Echinodermata	*Temnotrema sculptum*		1	1.17	1.52	1.94	1.37	1.76	2.19	1.89	2.68	3.66
Miscellaneous	*Cibicides lobatulus*	viii	1	1.00	1.29	1.67	1.87	2.21	2.50	2.10	2.87	3.83
Miscellaneous	*Endeis nodosa*		2	1.11	1.41	1.78	1.69	2.04	2.38	2.06	2.88	3.82
Miscellaneous	*Gromia oviformis*		1	1.00	1.29	1.61	1.75	2.07	2.44	1.96	2.66	3.62
Miscellaneous	*Halacarellus schefferi*		1	1.07	1.42	1.82	1.29	1.67	2.08	1.61	2.37	3.33
Miscellaneous	*Phascolosoma scolops*		3	1.50	1.83	2.17	1.69	2.06	2.44	2.80	3.77	4.75
Miscellaneous	*Telmatogeton japonicus*		3	1.22	1.54	1.94	1.56	1.97	2.38	2.24	3.04	4.09

Appendix 15-1. Species by ecoregion showing breakdown of risk scores (cont'd)

				Hawaii								
				Adjusted IMPACT			**Adjusted LIKELIHOOD**			**Adjusted CMIST SCORE**		
				Lower confidence limit	**Mean**	**Upper confidence limit**	**Lower confidence limit**	**Mean**	**Upper confidence limit**	**Lower confidence limit**	**Mean**	**Upper confidence limit**
Group	**Species**	**Footnote**	**Invasion history score**									
Mollusca	*Arca navicularis*		1	1.05	1.38	1.78	1.56	1.93	2.31	1.83	2.66	3.66
Mollusca	*Bankia bipennata*		1	1.11	1.47	1.89	1.50	1.92	2.31	1.91	2.83	4.00
Mollusca	*Bankia carinata*		1	1.11	1.48	1.89	1.56	1.92	2.31	2.00	2.84	3.91
Mollusca	*Barbatia virescens*	ix	1	1.05	1.38	1.78	1.62	2.00	2.38	2.00	2.75	3.75
Mollusca	*Crassostrea gigas*		3	1.81	2.14	2.45	1.99	2.34	2.63	4.02	5.03	6.03
Mollusca	*Crepidula onyx*		3	1.40	1.73	2.08	1.75	2.11	2.50	2.69	3.63	4.75
Mollusca	*Dendostrea folium*		2	1.16	1.53	1.89	1.74	2.16	2.50	2.44	3.30	4.41
Mollusca	*Dendronotus frondosus*		1	1.05	1.33	1.67	1.31	1.67	2.06	1.58	2.22	3.11
Mollusca	*Dolabella auricularia*		1	Native	Native	Native	Native	Native	Native	Native	Native	Native
Mollusca	*Hermissenda crassicornis*		1	1.11	1.39	1.78	1.44	1.75	2.19	1.74	2.44	3.24
Mollusca	*Hiatella orientalis*	x	2	1.11	1.45	1.84	1.56	1.95	2.38	2.04	2.82	3.78
Mollusca	*Hyotissa chemnitzi*		1	1.11	1.46	1.83	1.37	1.77	2.19	1.80	2.59	3.65
Mollusca	*Hyotissa numisma*		1	1.11	1.49	1.89	1.56	1.98	2.38	2.03	2.95	4.01
Mollusca	*Isognomon legumen*		1	1.05	1.38	1.78	1.75	2.10	2.50	2.08	2.89	3.89
Mollusca	*Laevichlamys irregularis*		1	1.11	1.46	1.89	1.56	1.95	2.38	1.96	2.84	3.98
Mollusca	*Limaria hakodatensis*		1	1.11	1.46	1.83	1.43	1.83	2.25	1.82	2.67	3.66
Mollusca	*Lithophaga curta*		1	1.11	1.44	1.83	1.37	1.79	2.13	1.77	2.57	3.55
Mollusca	*Lyrodus takanoshimensis*		3	1.22	1.57	1.95	1.50	1.87	2.32	2.06	2.93	4.11
Mollusca	*Mitrella moleculina*		1	1.11	1.46	1.89	1.44	1.87	2.31	1.83	2.73	3.78
Mollusca	*Mizuhopecten yessoensis*	xi	1	1.11	1.45	1.83	1.37	1.73	2.13	1.76	2.52	3.45
Mollusca	*Modiolarca cuprea*	xii	1	1.11	1.47	1.90	1.44	1.82	2.19	1.83	2.67	3.76
Mollusca	*Modiolus nipponicus*		1	1.05	1.37	1.80	1.50	1.90	2.31	1.78	2.60	3.61
Mollusca	*Mopalia seta*		1	1.11	1.45	1.83	1.31	1.68	2.06	1.71	2.44	3.43
Mollusca	*Mytilisepta virgata*	xiii	1	1.10	1.43	1.78	1.37	1.82	2.19	1.81	2.61	3.59
Mollusca	*Mytilus coruscus*	xiv	1	1.11	1.37	1.73	1.56	1.95	2.31	1.92	2.67	3.53
Mollusca	*Mytilus galloprovincialis*		3	2.28	2.55	2.83	1.92	2.28	2.63	4.78	5.82	6.97
Mollusca	*Mytilus trossulus*		1	1.29	1.67	2.00	1.71	2.05	2.42	2.55	3.49	4.48
Mollusca	*Nipponacmea habei*		1	1.11	1.48	1.89	1.25	1.69	2.13	1.67	2.50	3.54
Mollusca	*Pascahinnites coruscans*		1	1.11	1.47	1.89	1.69	2.06	2.44	2.19	3.03	4.11
Mollusca	*Pinctada imbricata*		1	1.16	1.44	1.78	1.62	1.96	2.38	2.03	2.83	3.75
Mollusca	*Reishia bronni*	xv	1	1.16	1.52	1.95	1.37	1.77	2.19	1.89	2.70	3.66
Mollusca	*Scaeochlamys squamata*		1	1.11	1.48	1.89	1.50	1.91	2.38	1.98	2.83	3.78
Mollusca	*Sphenia coreanica*		3	1.22	1.59	2.00	1.87	2.21	2.57	2.58	3.52	4.63
Mollusca	*Spondylus cruentus*	xvi	1	1.11	1.46	1.83	1.37	1.79	2.25	1.81	2.61	3.66
Mollusca	*Teredo navalis*		3	1.33	1.67	2.04	1.75	2.13	2.50	2.64	3.55	4.51
Mollusca	*Teredothyra smithi*		1	1.11	1.44	1.83	1.44	1.85	2.25	1.85	2.67	3.72
Nemertea	*Oerstedia dorsalis*		1	1.17	1.47	1.78	1.37	1.72	2.13	1.77	2.54	3.45
Nemertea	*Quasitetrastemma nigrifrons*	xvii	1	1.06	1.37	1.72	1.37	1.77	2.19	1.70	2.42	3.33

Now in JTMD list under name in column, but searched as:

i *Arabella semimaculata*
ii *Arbocuspis bellula*
iv *Membranipora serrilamella*
vi *Harpacticus pacificus*
xii *Musculus cupreus*
xi *Patinopecten yessoensis*
xiii *Septifer virgatus*
xvii *Tetrastemma nigrifrons*

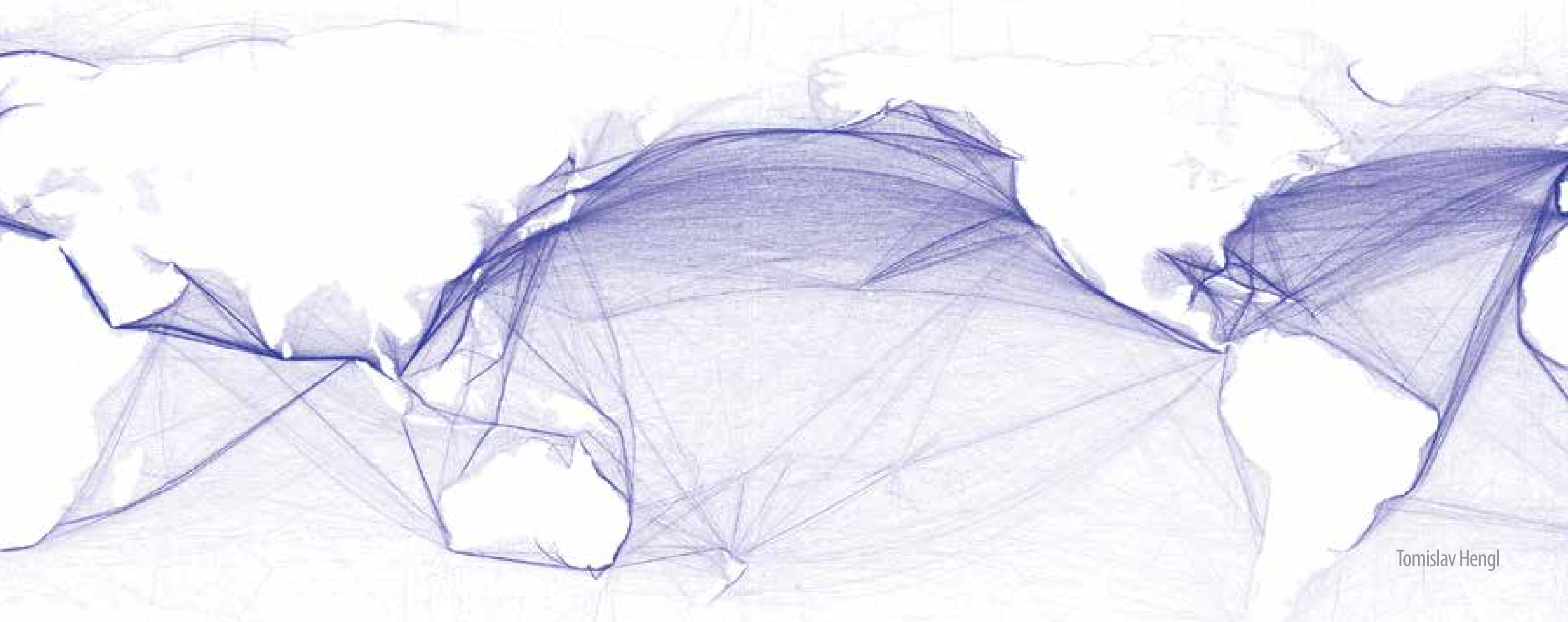
In JTMD list under name in column, but referred to in marinespecies.org as:

iii *Cauloramphus spiniferum* (Johnston 1832)
v *Orthopyxis crenata* (Hartlaub 1901)
viii *Lobatula lobatula* (Walker & Jacob 1798)
x *Hiatella arctica* (Linnaeus 1767)
xiv *Mytilus unguiculatus* (Valenciennes 1858)
xvi *Spondylus squamosus* (Schreibers 1793)

Retained as name in column due to similarities in data, but searched as:

iii *Cauloramphus cryptoarmatus*
vii *Harpacticus flexus*
xv *Reishia clavigera*
ix *Barbatia foliata*


U.S. Navy


Tomislav Hengl

THEME VI – Risk of Invasion

Chapter 16: An evaluation of Japanese Tsunami Marine Debris as a potential vector of invasive species

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Abstract

The influx of debris from the Great Japan Tsunami of 2011 carries with it the possibility of introducing invasive species. This was a unique, single-time event that is already declining in intensity. We conducted a qualitative vector risk assessment to compare Japanese Tsunami Marine Debris (JTMD) to other important marine invasion vectors, both current and historical, in the North Pacific: ballast water, hull fouling, aquaculture and ornamental trade. A risk assessment model based on Williams et al. (2013) was used to evaluate JTMD against other contemporary vectors. Eight variables relating to four different stages of the invasion process: source, transit, delivery, and impact were used to compare vectors. These variables included: (1) entrainment with the vector, (2) species richness per shipment, (3) number of shipments, (4) abundance per shipment, (5) survivorship potential, (6) shipment duration, (7) release to environment, and (8) environment match.

Three of these variables could not be ranked due to the unavailable data for JTMD (4 – abundance per shipment, 5 – survival potential) or inapplicability to this novel vector (6 – shipment duration). Of the variables evaluated, JTMD scored *High* for three of the risk variables: (1) entrainment with the vector, (3) number of shipments, (7) release to environment; all other variables were scored *Low* or *Medium*. The other North Pacific vectors assessed included more high-risk variables. From this comparison, we conclude that JTMD is most similar to hull fouling.

By examining the JTMD vector, we identified additional cross-vector comparative variables that are not accounted for in the original Williams et al. (2013) model. JTMD differs from contemporary vectors in (9) species assemblage distinctness (i.e., the number of novel taxa associated largely or only with a specific vector), (10) recipient habitat diversity (i.e., the diversity of target region habitats exposed to a vector), (11) the diversity of physical entry points (i.e., typically a single point of port entry for ships vs. multiple unpredictable haphazard landings for JTMD), (12) the frequency of repetitive arrivals and releases into the receiving environment of reproductive adults, and (13) the length of post-arrival residency of alien reproductive adult populations. A number of higher-risk species associated with JTMD have previously been introduced to at least one ecoregion in Pacific North America. There is some overlap with the species found on JTMD and those associated with these other vectors, but the majority of JTMD species have not been sampled in any other vectors, historical or contemporary, making prediction of establishment and impact difficult.


CSIRO Marine Research

Introduction

The Great Japan Tsunami of 2011 washed an estimated 5 million tons of debris into the Pacific Ocean. This debris differs from historical and natural marine debris in that the anthropogenic materials (such as plastic, fiberglass, Styrofoam, and preserved wood) are largely non-biodegradable, which allows these materials to reach distant shores without degrading appreciably. When Japanese Tsunami Marine Debris (JTMD) began arriving in Pacific North America and Hawaii, it was discovered that living coastal Japanese species were attached or entrained (see Chapters 7 to 10), highlighting the potential for JTMD to introduce invasive species. However, other known vectors of invasive species have been operating in the North Pacific for centuries and have previously introduced hundreds of species to North America and Hawaii (Ruiz et al., 2015).

Oyster aquaculture, commercial shipping, and the bait and aquarium trade collectively are responsible for more than 450 species introductions to North America since the 1800s (Ruiz et al., 2015). The import of oysters for aquaculture purposes has been cited as possibly the single greatest vector of introduced species worldwide (Ruesink et al., 2005). Commercial imports of live oyster seed and adults to the Pacific coast of North America began in the 1880s and continued unregulated until the 1930s (Wonham and Carlton, 2005). This vector intentionally introduced *Crassostrea gigas* (Thunberg 1793) from Asia and *Crassostrea virginica* (Gmelin 1791) from Atlantic Canada and is believed to be responsible for dozens of associated hitchhiking introductions, including the invasive oyster drill snail (*Ocinebrellus inornatus* Récluz 1851), mud snail (*Batillaria attramentaria* G. B. Sowerby I 1855), and wireweed (*Sargassum muticum*), among others (Levings et al., 2002; Ruiz et al., 2011). Policies such as the ICES Code of Practice on the Introductions and Transfers of Marine Organisms in the 1970s and Canadian Fishery Regulations reduced the number of species introduced for aquaculture or other purposes (Fisheries and Oceans Canada, 2003; ICES, 2005), and this vector is now managed in an effort to prevent the introduction of unwanted hitchhikers.

Commercial shipping is considered one of the most important pathways for species introductions, both historically and in modern times (Fofonoff et al., 2003). Non-indigenous species (NIS) have been detected with commercial shipping in ballast water and sediments (Lavoie, 1999; Hayes and Hewitt, 2000; MacIsaac et al., 2002; Levings et al., 2004; Flagella et al., 2007), with hull fouling (Gollasch, 2002; Godwin, 2003; Coutts and Taylor, 2004; Lewis et al., 2004; Drake and Lodge, 2007; Sylvester et al., 2011) and sea chests (Godwin, 2003; Coutts and Taylor, 2004; Coutts et al., 2007; Frey et al., 2009). Despite the implementation of mid-ocean ballast water exchange regulations in 2004, coastal organisms continue to be detected in ballast water tanks (Levings et al., 2004; Scriven et al., 2015; Cohen et al., 2017).

Recent studies on the recreational boating vector have shown that hull fouling contributes to the spread of NIS in North America and globally (Davidson et al., 2010; Clarke Murray et al., 2011, 2014; Ashton et al., 2014; Zabin et al., 2014). Additionally, the import of species for ornamental, seafood, bait and research activities has contributed to the introduction of species to North America (COST, 2013; Williams et al., 2013). Biological sampling of the species associated with these vectors is relatively rare, and species may be carried by more than one vector. In many cases it is difficult to assign a single vector as the source of a documented invasion (Ruiz et al., 2015).

Risk assessment is an important tool that can inform policy and management decisions about NIS. In order to evaluate the risk from potential invasive species transported by JTMD, a vector risk assessment was conducted in this study. There is an abundance of risk assessment models available for species-specific evaluation and prioritization (reviewed in Dahlstrom et al., 2011). A screening-level risk assessment tool was applied to each species found associated with JTMD (see Chapter 15) using a database of life history traits and invasion histories. However, comparing the JTMD vector to other important vectors operating in an increasingly connected Pacific Ocean requires a conceptual framework. We developed a risk assessment framework to evaluate the risk of JTMD as a vector for invasive species. This vector draws on the results of the modeling, monitoring and biodiversity research. Specifically, the model can be used to inform and prioritize monitoring, research, and cleanup efforts in response to the debris resulting from the Great Japan Tsunami of 2011. Further, this process will create a general vector risk assessment model that can be applied at various scales to inform management of marine and terrestrial vectors of NIS.

Here we review the evidence acquired about the JTMD vector during the ADRIFT (Assessing the Debris-Related Impact From the Tsunami) project and compare the risk of species introduction by JTMD to risks associated with other vectors. We ask specifically, "What makes the JTMD vector different from other historical and contemporary vectors of NIS? Which vectors are most similar? Ultimately, does JTMD pose a higher risk than other contemporary vectors of NIS in Pacific North America?"

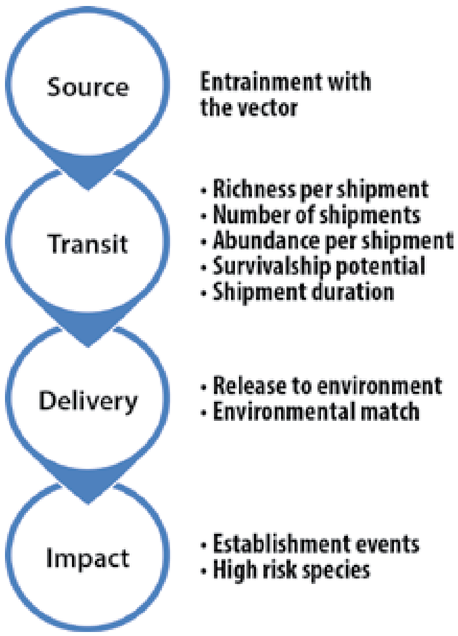

Figure 16-1. Invasion flow diagram showing the stages of the invasion process (Source, Transit, Delivery and Impact) and the component variables (adapted from Williams et al., 2013 and COST, 2013).

Methods

Risk can be defined as a function of Exposure (or likelihood) and Consequence (or Impact). Here we adapted the Williams et al. (2013) and California Ocean Science Trust (COST, 2013) frameworks, which are qualitative risk frameworks to compare characteristics and behaviours among NIS vectors. Both frameworks were designed to evaluate vectors in California but are broadly applicable to other regions and vectors. The framework follows the invasion process, with variables characterizing each step from source to transit, delivery, and impact (Figure 16-1; Table 16-1). Where Source is the potential for species entrainment with the vector, Transit is the shipment characteristics and transport survival, and Delivery is release to the environment and environment match with the receiving environment. The definitions for the scoring rubric for each variable (Low-Medium-High) are shown in Table 16-1. Impact is not explicitly scored as part of the current risk assessment but is represented here by the presence of high-risk species and records of establishment.

For each variable in the invasion framework we compile and discuss the evidence of JTMD as a vector of potentially invasive species and then compare this to the other vectors currently operating in the North Pacific: ballast water, hull fouling, aquaculture, and ornamental trade, as well as historical oyster aquaculture and ballast water movements. Ecoregions described here are the Marine Ecoregions of the World from Spalding et al. (2007).

Table 16-1. Scoring guide to variables used in vector risk assessment (adapted from COST, 2013).

Variable	Definition	Scale
Entrainment with the vector	Total number of species inhabiting source locations	Low < 100 species Medium 100–1,000 species High > 1,000 species
Richness per shipment	Total number of unique species in a shipment	Low < 9 species Medium 10–100 species High > 100 species
Number of shipments	Number of shipments into the study region	Low < 100 Medium 100–1,000 High > 1,000
Abundance per shipment	Number of individuals that enter the study region, per shipment	Low < 1,000 Medium 1,000–10,000 High > 10,000
Survival potential	The proportion of entrained NIS that is likely to survive transport based on the nature of the vector environment	Low < 5% Medium 5–95% High > 95%
Shipment duration	Vector transit time as it relates to potential exposure of NIS to study region marine waters	Low > 2 weeks Medium ≥ 1 day ≤ 2 weeks High ≤ 1 day
Release to environment	Percentage of organisms in a given shipment that are likely to have contact with study region marine waters	Low < 10% Medium 10–95% High > 95%
Environmental match	Likelihood that an NIS will reach an environment that has similar physical or chemical conditions to its native habitat.	Low < 5% Medium 5–95% High > 95%

Results and Discussion

Source

Entrainment with the vector

The JTMD vector

Entrainment with the vector was evaluated using a literature review of the diversity of the species and field surveys of the fouling community in the Tohoku region of Japan. Unlike other vectors, there is a single source country for the JTMD vector – Japan. The Tohoku region has been the focus of intense marine biodiversity research and is known to host thousands of species (Fujikara et al., 2010). Unfortunately, the total number of species available to colonize tsunami debris items after the event is unknown.

The Tohoku fouling panel survey aimed to obtain a collection of fouling organisms in Japan to morphologically and genetically complement the existing collection of JTMD species. A survey of the fouling invertebrates was conducted at five sites in the Tohoku region in 2015 and 2016 by Japan NUS Co., Ltd. and colleagues (see Chapter 8). The total species richness identified across all locations was 95 species (or morphospecies). The final list of species found in each survey is shown in Chapter 8, Appendix 8-1. The mean species richness per plate, across all sites and seasons, was 19 species; plate species richness ranged from 8 to 35 species (Table 16-2). The total richness of the fouling species varied depending on the location. Species richness was highest in the most southern location, Matsushima (63 species), followed by Kesennuma (36 species), and the lowest richness was documented in the most northern location, Miyako (31 species).

More species were detected in the second survey than the first survey at all sites. Phylum Arthropoda (especially Class Malacostraca) dominated at all sites. It should be noted that suspended fouling panels sample only a subset of the available biodiversity in an area (Gartner et al., 2016). While they are a reasonable approximation of the colonization of marine debris, they will not capture all species in a location that could have colonized JTMD. Seasonality, inter-annual variability, and the unique conditions after the tsunami make replication difficult.

Evidence from the literature and the fouling surveys in the tsunami region showed that the available species diversity was substantial. Therefore, the JTMD vector score for the cumulative species richness variable is *High* (>1,000 species).

Vector comparison

As a proxy for number of available species for other vectors, the number of source countries was used to compare between vectors. All the other vectors of transport had more than a single source country. Commercial shipping to the USA and Canada came from more than 100 source countries making the score for both ballast water and hull fouling *High* (Table 16-3; Keller et al., 2011). Over the years the aquaculture industry in North America has imported culture species and associated hitchhikers from several areas including Asia, Europe, and the east coast of North America. Thus, the source pool is *High*. The ornamental vector originates from a diversity of source regions and therefore, the score is *High*.

Transit

Richness per shipment

The JTMD vector

The total number of unique species in a shipment was evaluated using the JTMD biofouling database as well as accumulation curves and estimates of the asymptote to predict cumulative species richness across all debris items. JTMD items were sampled for biological material, and samples retained for morphological and genetic analyses (see Chapters 7 to 10). In total, 634 items were sampled. The mean invertebrate species richness across all sampled JTMD items was 4.8 species and ranged from 0 to 118 species per item. While data on the algae species richness per item were not available for this summary, the highest number of species was found on the Misawa-1 dock; this item had 131 invertebrate and algae species. The data are highly skewed towards small numbers of species, and the overall median is two species (Figure 16-2). The upper quartile of richness was four species, making the score for JTMD richness *Low* (< 9 species). The total number of unique species sampled across the entire JTMD debris pool (634 items) was 316: 233 invertebrates, 80 algae and 2 fish species (see Chapters 7 and 9).

Not all species present on all debris items were sampled. Some items had systematic sampling of all biota, while others were just a handful of mussels. Researchers differentiated the sampling effort, designating items with exhaustive sampling High Resolution (HR), as opposed to others that were more haphazard. Rarefaction and local richness estimation analysis of the species accumulation curve was conducted for JTMD. The analysis was based on the 108 JTMD items that were considered to be well sampled for biological richness (HR items; see Chapter 7). The results estimate that the maximum species richness is 503 species (+/– 50 SE) (Chao estimate; Figure 16-3). This number may be an overestimate as only those debris items with Japanese biological material were catalogued.

While there was extensive biological sampling of JTMD items when possible, this was a relatively small proportion of the debris field that landed in Pacific North America and Hawaii. Not all JTMD items were identified as such and not all JTMD items were sampled biologically, creating spatial and temporal biases in the data. The degree of sampling error is unknown in that debris items may have landed on inaccessible and/or uninhabited stretches of beach, particularly in northern British Columbia, Hawaii and Alaska. The majority of the biological samples came from landings in Washington and Oregon, where researchers were located and there is a high coastal human population. Additionally, there was a temporal bias in that there were more JTMD sightings and recognition in years immediately following the event and decreasing over time.

Table 16-2. Tohoku coast survey site and documented species richness.

Site	Mean species richness	Minimum species richness	Max species richness	Total species richness
Kesennuma	19.0	14	24	36
Matsushima	26.9	13	35	63
Minamisanriku	15.4	12	21	51
Miyako	17.3	8	27	31
Overall	**19.3**	**8**	**35**	**95**

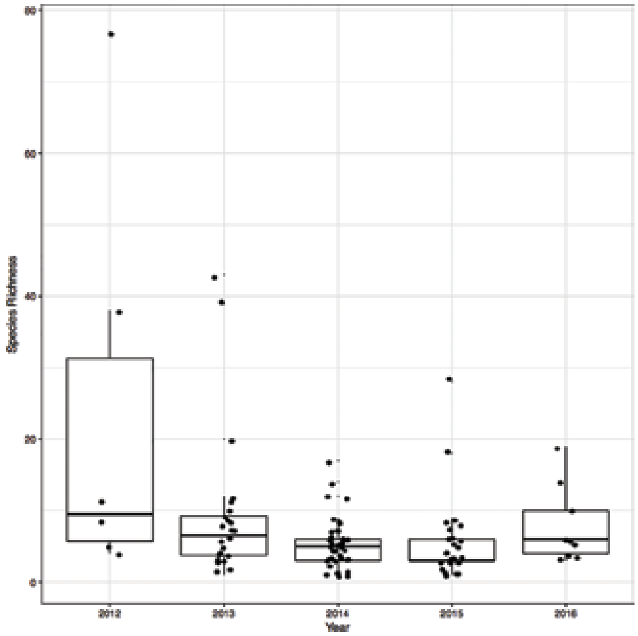

Figure 16-2. Box-and-whiskers plot of invertebrate species richness per item on sampled JTMD items (High Resolution items only). The box encloses the 1st and 3rd quartiles and the black filled circles represent individual debris items. Bold horizontal line is the median species richness. Data last updated October 2016.

Table 16-3. Top destination ports for each ecoregion, showing number of origin port countries from Lloyd's Maritime Intelligence Unit (2005–2006) (data from Keller et al., 2011, Table S4).

Country	Destination port	Ecoregion	Origin port countries
USA	Valdez, Alaska	Gulf of Alaska	21
USA	Seward, Alaska	Gulf of Alaska	19
USA	Anchorage, Alaska	Gulf of Alaska	18
USA	Kodiak, Alaska	Gulf of Alaska	15
USA	Sitka, Alaska	Pacific North American Fijordland	19
Canada	Prince Rupert, British Columbia	Pacific North American Fijordland	65
Canada	Kitimat, British Columbia	Pacific North American Fijordland	34
Canada	Stewart, British Columbia	Pacific North American Fijordland	15
USA	Juneau, Alaska	Pacific North American Fijordland	21
USA	Ketchikan, Alaska	Pacific North American Fijordland	20
USA	Astoria, Oregon	Oregon, Washington, Vancouver coast and shelf	99
USA	Portland, Oregon	Oregon, Washington, Vancouver coast and shelf	73
USA	Newport, Oregon	Oregon, Washington, Vancouver coast and shelf	71
USA	Coos Bay, Oregon	Oregon, Washington, Vancouver coast and shelf	21
USA	San Francisco, California	Northern California	146
USA	Sacramento, California	Northern California	23
USA	Honolulu, Hawaii	Hawaii	118
USA	Hilo, Hawaii	Hawaii	19
USA	Kailua-Kona, Hawaii	Hawaii	12


Cathryn Clarke Murray

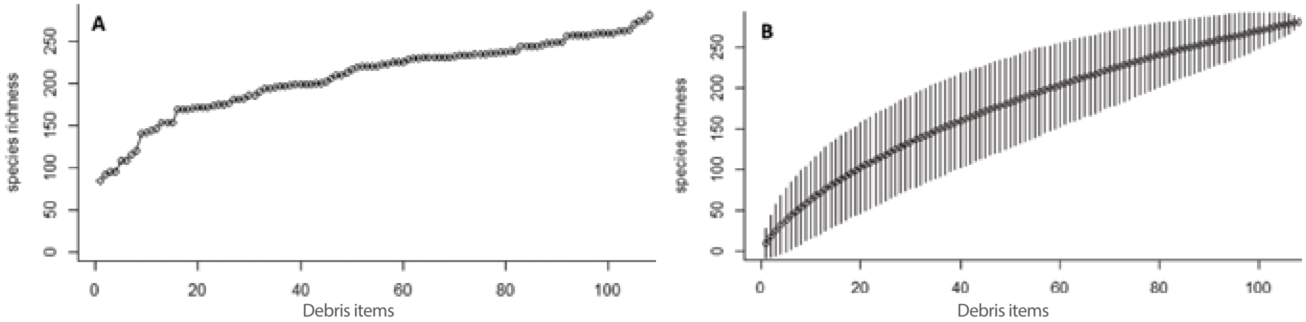

Figure 16-3. (A) Species accumulation curve and (B) rarefaction plot of the species richness for 108 High Resolution JTMD items. Data last updated October 2016.

Vector comparison

Ships originating from Japan sampled in Coos Bay, Oregon, had a total of 367 taxa recorded from the ballast water of 159 ships (Carlton and Geller, 1993). No ship-specific information was available. At the Port of Vancouver, Canada, DiBacco et al. (2011) identified 176 zooplankton taxa from the ballast water samples of 70 vessels, and Casas-Monroy et al. (2014) identified 184 zooplankton and phytoplankton taxa from 70 vessels. Levings et al. (2004) sampled 15 ships in Vancouver Harbour, and identified 65 taxa. Therefore, the overall score for ballast water species richness is *High* (> 100 species).

Commercial hull fouling studies showed that there were 141 taxa sampled from the hull fouling communities of 20 vessels in Vancouver Harbour (Sylvester et al., 2011). The median species richness per ship was 34 species, and the upper quartile was 62 species. Vessels sampled in San Francisco Bay, California, had a total of 34 species identified from five ships. Species richness per ship ranged between 6 and 20 (Davidson et al., 2009). In Hawaii, 83 unique taxa were identified from eight vessels, the median species richness per ship was 8 species and ranged from 0 to 33 species (Godwin et al., 2003). The upper quartile species richness was 15 species. Therefore, the overall score for shipment richness in commercial hull fouling is *Medium* (10–100 species).

Aquaculture carries much lower species richness per shipment under current management and regulations, typically less than 5 species (COST, 2013), and the score is *Low*. Historical aquaculture had much higher species richness per shipment, and the score is *Medium* (Williams et al., 2013). The ornamental vector has high species richness per shipment (Williams et al., 2013), and the score is ranked *Medium*.

Number of shipments

The JTMD vector

The number of shipments arriving at a destination per year was evaluated using evidence from the JTMD biofouling database, disaster debris sightings, and modeling estimates. The frequency of delivery should increase the chances of an NIS successfully establishing in the new environment. While the precise number of debris items from the tsunami that arrived on Pacific North American and Hawaiian coastlines is difficult to estimate, we have several data sources to use in the qualitative ranking of this variable. The original estimate from the Government of Japan suggests that 1.5 million tons of debris remained floating after the tsunami. There is a significant background amount of marine debris in the North Pacific that is completely unrelated to the tsunami. Distinguishing tsunami debris from general marine debris was difficult in most cases. Debris items with registration numbers, such as vessels, and other identifying marks were the highest level of confirmation.

More than 630 objects were registered in the JTMD biofouling database (see Chapter 7 for rationale). Reports to the NOAA disaster debris reporting system[1] totaled more than 1,600 items, with 60 of these officially confirmed as lost during the tsunami (Table 16-4). Monitoring surveys recorded a 10-fold increase in indicator items in the years after tsunami debris began arriving, and at surveyed beaches the cumulative number of debris items counted between 2012 and 2015 was almost 100,000 (see Chapter 3). Modelling results estimated that 1,000 small boats were lost to the North Pacific with the tsunami and that 300 to 500 may still be floating in the North Pacific (see Chapter 2).

Based on this evidence, the number of shipments associated with JTMD is ranked *High*, and more than 1,000 shipments arrived on the Pacific North American and Hawaiian shorelines each year. Note that documented tsunami debris items have been steadily declining, after the peak in 2013–2014 (see Chapters 3 and 7), and we expect this decline to continue such that in future years this variable likely would score lower. This further highlights the unique nature of JTMD as a vector representing a single event resulting in multiple shipments per year, rather than ongoing activities that result in continuing shipments per year.

Vector comparison

Commercial shipping represents thousands of ships arriving at major ports in North America on an annual basis. Casas-Monroy et al. (2014) reported 1,488 international ballast water discharge events for vessels arriving at the Port of Vancouver in a single year (2008), recognizing that some deballasting occurs as vessels near the actual port. Commercial shipping ballast water and hull fouling were ranked *High* (> 1,000). Aquaculture shipments were ranked *Medium* (100–1,000) and ornamental shipments were ranked *High* (Williams et al., 2013).

Abundance per shipment

The JTMD vector

Abundance per shipment refers to the number of individuals that enter the destination region per shipment (upper quartile). This characteristic is measured because transferring more individuals in a single shipment will increase the likelihood that an NIS successfully establishes a population in the new environment. Some analysis of abundance was conducted for model organisms – mussels (*Mytilus galloprovincialis*) and peracaridan crustaceans (see Chapter 11). For those items with more than 15 individuals, growth and reproductive characteristics were recorded (Miller et al., unpublished data). For this subset of items, the median abundance of *Mytilus* was 27 individuals and the upper quartile was 43.5 individuals. For peracaridan crustaceans, hundreds of individuals were found on the sampled JTMD items (see Chapter 11). As the abundance was not recorded systematically for all debris items, this variable is not ranked here.

Table 16-4. NOAA disaster debris reports by ecoregion and whether they were formally confirmed as JTMD*.

Ecoregion name	**Count**	**Confirmed JTMD**
Eastern Bering Sea	3	0
Aleutian Islands	1	0
Gulf of Alaska	78	4
Pacific North American Fijordland	49	3
Puget Trough/Georgia Basin	60	0
Oregon, Washington, Vancouver coast and shelf	849	21
Northern California	97	1
Southern California Bight	17	0
Hawaii	352	26
No geographic information available	121	5
Total	**1,627**	**60**

* Updated April 2016.

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[1] https://marinedebris.noaa.gov/current-efforts/emergency-response


Jessica Miller

Vector comparison

Ballast water is known to carry high abundances of individuals. Casas-Monroy et al. (2014, 2015) reported median abundance of zooplankton (individuals per m^3) and phytoplankton (cells per m^3) of Pacific International Transoceanic ships ($N = 23$) arriving at the Port of Vancouver harbour to be 1.8×10^3 and 1.81×10^5, respectively. Ships arriving into the Port of Vancouver had a total of 3.7×10^4 organisms in a single ballast water sample (Levings et al., 2004) although data were not presented in aggregate for comparison. Ballast water sampled from ships arriving in Coos Bay, Oregon, had certain taxa in high densities: copepod densities were greater than 1.5×10^3 individuals per m^3 and spionid polychaete larvae, barnacle nauplii, and bivalve veligers were greater than 2×10^2 per m^3 (Carlton and Geller, 1993). Based on this evidence, the score for abundance per shipment of ballast water is *High* (> 10,000).

The abundance of organisms associated with commercial hull fouling is difficult to estimate. There is extreme variation in cleaning practices and the application of antifouling paints that reduce fouling. There is also variation within a ship as niche areas can have considerable fouling even on relatively clean ships (Coutts and Taylor, 2004). Many of the species associated with fouling are encrusting or colonial species that are better represented by percent cover. The abundance per shipment for hull fouling is ranked *Medium* (1,000–10,000). Abundance of organisms per shipment in the aquaculture vector was estimated to be 150,000 individuals; therefore, the score is *High* (> 10,000) (COST, 2013). Ornamental shipments to California distributors were estimated to include 100,000 individuals (COST, 2013), and the score is *High* (> 10,000).

Transport survival

Survival potential (quality of the vector environment)

The JTMD vector

Survival potential is defined as the proportion of entrained NIS that are likely to survive transport based on the nature of the vector environment. This variable is important because the vector environment conditions during transport influence the likelihood of organism survival. For JTMD, this variable is difficult to assign a score because there are no biological samples from floating JTMD items in the eastern Pacific Ocean or even from items prior to landing in North America or Hawaii. A comparison between the species identified from fouling panels deployed in the Tohoku region for 90 days and those on JTMD suggest that only 34% of species found on JTMD are a match, or possible match, to those on the Tohoku fouling panels (see Chapters 7 and 8).

Differences in growth and survival of model species, such as *Mytilus*, suggest that the voyage duration and route had some effect on the fitness of JTMD organisms (see Chapter 11). Mussels arriving in the Hawaiian Islands were smaller, and fewer were reproductive, suggesting that the voyage had less than ideal conditions. Isotope analysis of mussel shell growth does indicate that mussels had the ability to grow during the JTMD voyage. Additionally, some species of peracaridan crustaceans were able to self-recruit to JTMD items and maintain their populations during the voyage. Data for this variable are acutely limited in both time (over the 5+ year JTMD vector duration period) and space (over than 500 km coastal source environment) relative to the initial composition of biofouling communities both colonizing debris and departing Japan. Therefore, this variable was not ranked for JTMD.

Vector comparison

Survival of organisms associated with ballast water is highly variable. Differences have been observed between exchanged and unexchanged ballast tanks, between ship types, regions, and time of voyage. Different taxa vary in survivorship of conditions in ballast water as well. In general, the abundance of ballast water organisms decreases during a voyage but as Briski et al. (2013) highlight, this can be region and taxa specific. Lavoie et al. (1999) reported that less than 40% of the original abundance remained at the end of even very short (<36 hours) intracoastal voyages. Therefore, the survival of ballast water organisms is scored *Medium* (5–95% survival).

Survivorship with hull fouling is largely unknown. There may only be a single published study on voyage survival for obsolete vessels (Davidson et al., 2008) and one for commercial hull fouling (Coutts et al., 2009). Coutts et al. (2009) reported decreasing percent cover with increasing speed, with largest decreases at higher speeds. At 10 and 18 knots (~18.5 and ~33 km h^{-1}), percent cover was reduced by 24 and 85%, respectively. Based on experimental results, Clarke Murray et al. (2012) demonstrated that many common fouling species are capable of withstanding vessel speeds much higher than floating debris would travel. Davidson et al.'s (2008) study of two obsolete vessels showed significant decrease in percent cover of some taxa, especially branching bryozoans and barnacles. The proportion of dead barnacles increased approximately 40% pre- and post-voyage. The hull fouling survivorship score for hull fouling on both recreational and commercial vessels is therefore *Medium* (5–95%).

Other vectors that transport organisms with the intention of keeping them alive have higher survivorship probabilities (Williams et al., 2013). The ornamental and aquaculture vectors therefore, are both scored *High* (> 95%) for this variable.

Shipment duration (from last port of call)

The JTMD vector

Shipment duration refers to vector transit time, which relates to potential exposure of NIS to destination marine waters. Shorter transport time should result in organisms arriving in better physiological condition, which improves their chances of survival. Based on all objects categorized as JTMD, as of July 20, 2016, voyage duration ranged from 0.9 to 4.8 years and still counting (Figure 16-4a). The mean duration across the 410 objects was 3.1 years. The latest JTMD objects to arrive have been at sea for almost 6 years and had living Japanese species aboard. There was a difference in voyage duration between debris item types: bins and "other" debris types had the longest voyage duration, while the vessels and two Misawa docks had the shortest (Figure 16-4b). Even the highest windage items took months to reach the shores of Pacific North America. The original Williams et al. (2013) model assumed that any shipment that took longer than 2 weeks would be low risk; however, this variable does not hold for JTMD, given the ability of species to survive for more than 4 years. Therefore, this variable is not ranked.

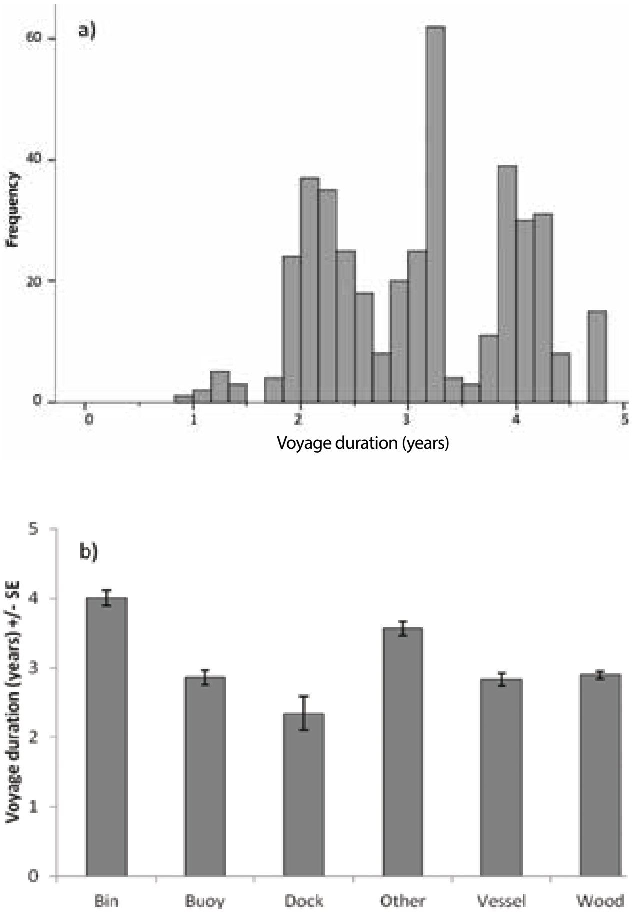

Figure 16-4. (a) Voyage duration (years) for all debris items and (b) JTMD item types.

Vector comparison

Ballast water studies of transoceanic voyages from Japan to Coos Bay showed that voyages ranged from 11 to 21 days (average 15.1 (SD 1.9) days). These trips are the most relevant to the JTMD vector comparison but ships from other regions or other types of ships may be shorter or longer in duration (Keller et al., 2010). The voyage duration score for ballast water is *Medium* (>1 day but < 2 weeks). Vectors transporting live organisms operate at much higher speeds, often utilizing air travel. Ornamental and aquaculture vectors have voyage times between 24 and 48 hours (Williams et al., 2013) and are given a score of *High* (≤ 1 day).

Delivery

Release to environment

The JTMD vector

Release to environment refers to the percentage of organisms in a given shipment that are likely to have contact with destination marine waters. This variable is considered because the likelihood an NIS introduction is increased if organisms will be in direct contact with destination marine waters. JTMD is similar to hull fouling in that species attached to, or associated with, JTMD are already immersed in the environment and do not require a release event to occur. Additionally, the landing of debris onshore may increase release and spread of attached organisms as the physical abrasion of landing may scrape off organisms. The score for release to environment for JTMD is therefore *High* (> 95%).

Nicolas Cegalerba

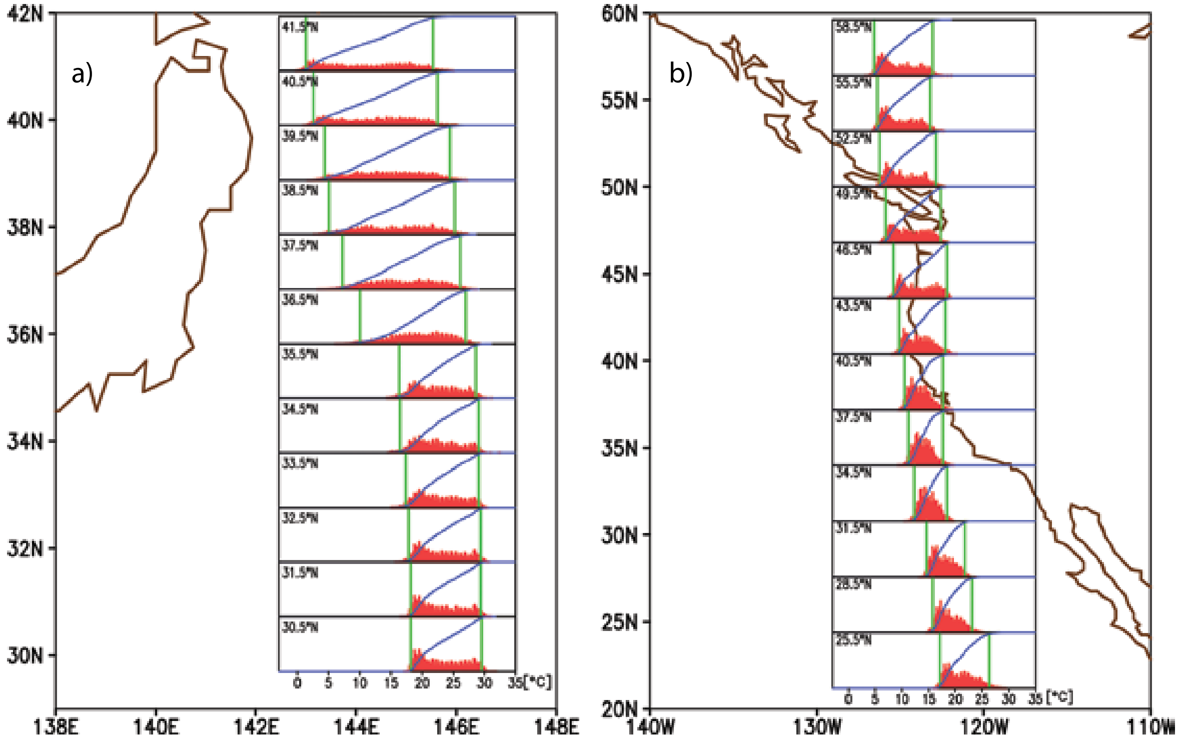

Figure 16-5. Probability density function (PDF; red bars) of sea surface temperature (SST) at different locations along (a) the east coast of Japan and (b) the Pacific coast of North America, calculated from Advanced Microwave Scanning Radiometer (AMSR) satellite data. Blue lines are cumulative PDFs and green bars indicate SST limits after removing outliers.

Vector comparison

Ballast water organisms are, by definition, confined to the ballast tanks but can be released when ballast water is exchanged or released. The tanks are not completely drained and cleaned, and some organisms may remain within the ballast tanks along with residual water and/or ballast sediments (sludges). Therefore, the score for ballast water is *Medium* (5–95%). Hull fouling organisms are already immersed in marine waters and thus, the score is *High* (> 95%). Species in the ornamental vector are not commonly released to the environment, although there is evidence that these incidents have occurred (Scott et al., 2013). The release to environment score for the ornamental vector is therefore *Low* (< 10%). Historical aquaculture often involved field transplant of imported adult oysters and modern aquaculture releases oyster larvae directly to the environment so the release to environment is *High* (> 95%).

Environmental match

The JTMD vector

Environmental match refers to the likelihood that an NIS will reach an environment that has similar physical or chemical conditions to its native habitat. The greater the similarity of chemical and ecological characteristics of the release environment to that of the native range of an introduced species, the higher the likelihood of its survival upon initial contact in receiving waters. The tsunami struck in the northeastern Honshu ecoregion, a cold temperate environment.

The ADRIFT modeling team calculated the climate match for temperatures in the North Pacific and their correspondence to the temperature statistics in the areas in Japan affected by the tsunami (see Chapter 2). Temperature is a critical parameter for the survival of marine species. Figure 16-5 shows how temperatures, observed by Advanced Microwave Scanning Radiometer (AMSR) satellite, change with latitude and differ on the western and eastern sides of the North Pacific. Importantly, the area in Japan located between 38° and 40°N and corresponding to the largest source of JTMD also has the broadest sea surface temperature (SST) range, reaching 20°C (Figure 16-6). This region has a very strong seasonal cycle with temperatures below 5°C in winter and above 25°C in summer. The SST range east of Japan exceeds the one in North America by as much as two times. Generally speaking, this means that coastal species that are able to survive in the ecoregion of northeastern Honshu may be resilient to temperature conditions practically anywhere in the North Pacific north of 30°N. The nearshore SST conditions between Baja California and Alaska all fit within the temperature range of the east coast of Japan, between 39° and 41°N.

The cumulative probability distributions for SST for the Pacific coast of North America north of 30°N range from a 0.3 to 0.8 probability match (Figure 16-7). This pattern does not include Hawaii, where tropical temperatures are significantly higher, suggesting that Japanese species from the north of Japan have a reduced environmental match. However, subtropical species such as the striped beakfish, associated with JTMD, could have been picked

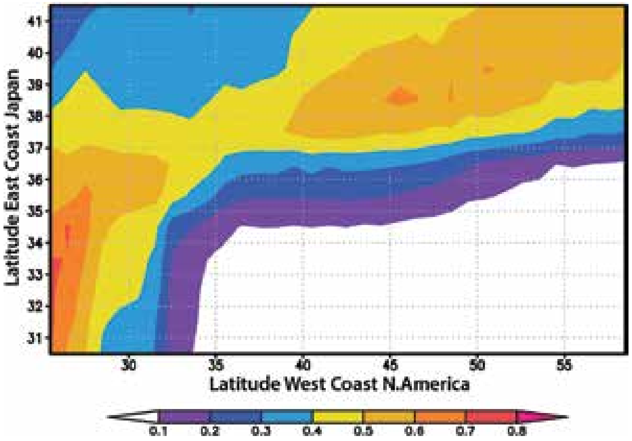

Figure 16-6. Cumulative probability distribution match for sea surface temperature (SST) range between the east coast of Japan and Pacific coast of North America.

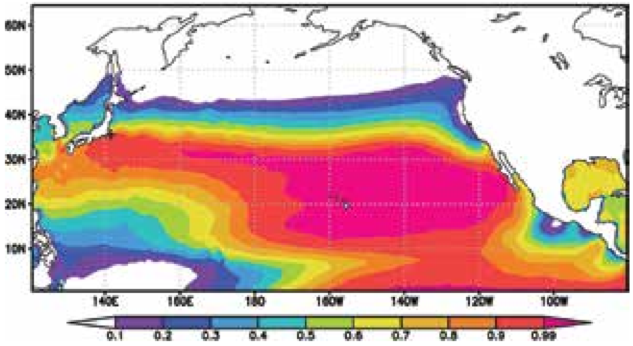

Figure 16-7. Degree of the sea surface temperature (SST) match with the climatology at selected southern location east of Japan (marked with cross) calculated using Advanced Microwave Scanning Radiometer (AMSR) satellite data.

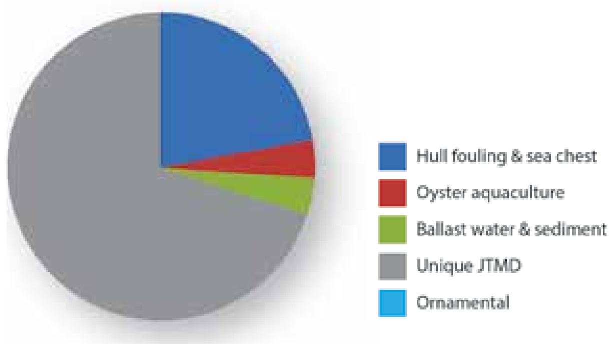

Figure 16-8. Community similarities between JTMD and other vectors: the percentage of genera recorded from each vector (hull fouling, oyster aquaculture, ballast water) which match that recorded from JTMD. Note that the ornamental vector had no genus or species in common with that from JTMD.

by JTMD in the Kuroshio Extension and these could have a higher match with SSTs in Hawaii (Figure 16-8). The overall score for environmental match for JTMD averaged across all recipient ecoregions is therefore *Medium* (5–95%).

Vector comparison

As with the source pool comparison, other vectors have a much wider range of source regions and therefore, are likely to have a larger range of climate match probabilities than that seen for the JTMD vector, which has a discrete and limited source range. Ballast water and hull fouling scores are *High* (>95%) (Williams et al., 2013). Aquaculture ensures a high probability of environmental match by releasing organisms in appropriate habitat and conditions. Thus, aquaculture also has a score of *High* (> 95%). Ornamental species are imported from tropical and/or freshwater habitats so the environmental match is likely to be *Low* (< 5%).

Impact of the vector

Species community associated with JTMD

Of the almost 300 species sampled from JTMD items, 21 species were also found in samples from other vectors (Table 16-5). Hull fouling has the most similar species community to that associated with JTMD. Hull fouling, including sea chests, had 15 species in common with JTMD (Godwin et al., 2004; Sylvester et al., 2011; Frey et al., 2014), oyster aquaculture had 4 species in common (Bonnot, 1935; Kincaid, 1947), and ballast water had 4 species in common with JTMD (Williams et al., 1988; Carlton and Geller, 1993; DiBacco et al., 2011). There were no species in common with the ornamental vector (Padilla and Williams, 2004). Overall, JTMD was most similar in species composition at the species and genus level to the hull fouling vector, while the next most similar vector was oyster aquaculture (Figure 16-8).

Though the JTMD species community was most similar to hull fouling, the percentage overlap was relatively small, even at the genus level (23%). The majority of the species documented in association with JTMD were unique (72%) and had never been documented in association with any other vector. JTMD brought a suite of grazers, the chitons and limpets, which have not been documented in association with any other vector past or present. The larger debris items were entire functioning ecosystems, from microalgae to large predators, some of which had self-sustaining populations. Thus, the JTMD vector is fundamentally different to other vectors in this regard.


Allan Pleus

Table 16-5. Species associated with JTMD that have been detected in studies of other vectors.

Phylum	JTMD species	Ballast water	Hull fouling	Aquaculture
Cnidaria	*Metridium dianthus*	X		
Cnidaria	*Obelia longissima*	X		
Annelida	*Harmothoe imbricata*		X	
Mollusca	*Mytilus galloprovincialis*	X	X	X
Mollusca	*Crassostrea gigas*		X	X
Mollusca	*Laevichlamys irregularis*			X
Mollusca	*Cellana toreuma*			X
Mollusca	*Reishia bronni*			X
Mollusca	*Acanthochitona achates*			X
Arthropoda	*Paralaophonte congenera*		X	
Arthropoda	*Conchoderma auritum*		X	
Arthropoda	*Balanus glandula*		X	
Arthropoda	*Balanus trigonus*		X	
Arthropoda	*Megabalanus rosa*		X	
Arthropoda	*Megabalanus zebra*		X	
Arthropoda	*Ampithoe valida*		X	X
Arthropoda	*Caprella equilibra*		X	
Arthropoda	*Caprella mutica*		X	
Arthropoda	*Jassa marmorata*-complex (includes *staudei, slatteryi*)	X	X	
Bryozoa	*Bugula stolonifera*		X	
Bryozoa	*Schizoporella japonica*		X	X

High-risk species associated with JTMD

The research on the risk of JTMD began with identifying species associated with arriving JTMD (see Chapters 7 to 10). In order to evaluate and prioritize higher-risk species associated with JTMD, a screening-level risk assessment was conducted (see Chapter 15). A database of species-specific traits and tolerances was designed to synthesize published literature on global invasion history, potential impacts, environmental tolerance, and reproductive and growth strategies for those species identified on JTMD (Appendix 12-2). Based on the information contained in the database, species risk assessments were conducted using a qualitative screening tool, the Canadian Marine Invasive Screening Tool (Drolet et al., 2016). The results yielded a list of higher-risk invaders for North America and Hawaii (see Chapter 15; Appendix 15-1). There were a number of high-risk species associated with JTMD, including well-known global invaders such as the mussel *Mytilus galloprovincialis*, the ascidian *Didemnum vexillum*, the sea star *Asterias amurensis*, and the algae *Undaria pinnatifida* and *Codium fragile fragile*. Additionally, the high-risk species *Didemnum vexillum* carried a hydroid parasite *Eutima* on JTMD objects; this parasite has not been detected in North America or Hawaii but has caused significant impacts in Japan (see Chapter 13).

Many of the notorious global invaders have been previously introduced to at least some of the ecoregions in Pacific North America and Hawaii by other vectors. However, a subset of species from JTMD has never been recorded outside their native Northwest Pacific range, and the probability of an introduction and invasion by these species is unknown. Some of these species have traits and characteristics that are similar to other species with known invasion history (see Chapter 12; Miller et al., 2018). Given the prevalence and continued operation of other vectors in all regions, it will be difficult to ascribe any new introductions definitively to JTMD, as the vector shares many characteristics with other vectors, in particular, hull fouling of recreational and commercial vessels and historical aquaculture imports.


Hideaki Maki

Establishment of JTMD species

An important component of the invasion process is that of establishment and spread. This stage is the most variable and difficult to predict, and the time lag between introduction events and detection of established populations can be years to decades in duration (Crooks et al., 1999). These time lags make it unlikely that any JTMD-associated establishment events would be detected at the conclusion of the ADRIFT project. However, surveys of fouling communities, natural habitat and mussels along western North America, detected no new invasions attributed to JTMD-mediated transport. Standardized surveys of invertebrate biofouling communities were conducted in California, Oregon, Washington, British Columbia, and Alaska (see Chapter 13). Timed search surveys were conducted for algae in natural habitats and floating structures in Alaska, British Columbia, Oregon, and Washington (see Chapter 14), and surveys to search for parasites detected in JTMD mussels were conducted from California to Alaska (see Chapter 13). Collectively these surveys have established a solid quantitative baseline and historical record to evaluate future invasions to assess whether JTMD is a plausible mechanism based on geographic distribution and other potential vectors.

In addition to the possibility of novel introductions of species from Japan via JTMD, there also exists the possibility of introduction of new genetic strains. Some JTMD species are known to be distributed on both sides of the Pacific Ocean either naturally or by anthropogenic introductions before the Great Japan Tsunami of 2011. Therefore, it was necessary to compare the three entities (i.e., Japanese natural populations, JTMD, and North American natural populations) by appropriate genetic markers (see Chapters 8 and 10). Among the JTMD taxa examined, some species are reported to be distributed on both sides of the North Pacific, and therefore, their new introduction to the shorelines of the Pacific coast of North America may not be regarded as a species-level invasion. However, our genetic comparisons indicated that some species are genetically distinct and may cause genetic contamination. Some species are already established in the Northeast Pacific by relatively recent anthropogenic introductions (e.g., *Undaria pinnatifida*), but have not been spread to all affected ecoregions, and had different haplotypes. Therefore, these new introductions will still pose a risk of accelerating the dispersal of these NIS, enrich the genetic diversity of the introduced populations, and further increase their competitiveness within the local populations.

While we conducted field and genetic surveys to detect new invasions, the sheer length of coastline and diversity of habitats would be nearly impossible to exhaustively search. The influx of JTMD occurred on stretches of mostly uninhabited, inaccessible coastline. Additionally, the surveys were conducted early in the invasion timeline and any successful invasions will likely not be detected for years to decades – the well-known time lag of invasion dynamics. Continued monitoring is recommended, using the baselines at key monitoring sites established here, for the years to come in order to fully understand the impact of this event.

Vector comparison

The establishment of species brought to North America by other vectors is well documented. The Smithsonian Environmental Research Center conducted a comprehensive review of NIS reported from Pacific North America and synthesized data in the National Exotic Marine and Estuarine Species Information System (NEMESIS)[2] databases through 2015. This served to evaluate the status of species detected in baseline surveys (above) as well as other species known to occur in North America. Over 50% of marine and estuarine NIS reported in Pacific North America also occur in Japan, when considering free-living invertebrates and algae, with roughly 30% native to Japan (Figure 16-9). Both the total number and percent overlap is smaller for known parasite species. Commercial ships have contributed 44% of the total introductions to the Pacific and Atlantic coasts of North America (200/450 NIS total), including species transferred primarily with ballast water or hull fouling (Figure 16-10; Ruiz et al., 2015).

Conclusions

JTMD represents a relatively rare phenomenon – a mega-pulse debris event. The intensity was relatively high initially, with many reported landings of items with non-indigenous species present, but as this phenomenon has unfolded, the intensity of this invasion vector has been declining. Specifically, the number of debris arrivals and species richness associated with JTMD items have all declined over the 5 years of study. The qualitative risk assessment conducted here shows that as a vector, JTMD is most similar to hull fouling of commercial shipping. This assessment shows that the JTMD vector ranks *Low* on one of the eight risk variables, *Medium* on two variables, and *High* on three of the variables – source, the number of shipments, and release to environment (Table 16-6). Two variables could not be ranked for JTMD. In contrast, all other marine vectors assessed had a greater number of *High* and *Medium* scores. Therefore, we conclude that compared to ballast water, hull fouling, aquaculture and the ornamental trade, JTMD poses a lower risk for the introduction of potentially invasive species to Pacific North America and Hawaii, which is in stark contrast to these other vectors that continue to operate (and in some cases are even increasing in intensity) (Keller et al., 2011; Ruiz et al., 2015).

The JTMD vector is most similar in risk to hull fouling (Table 16-6; Figure 16-11). Both vectors transport adult and sessile fouling organisms in fouling communities, have high probabilities for release to environment, and have the potential for survival in the receiving environment. However, JTMD differs in key variables from the modern transport of marine life by other vectors. JTMD has relatively low species richness and abundance per shipment, with most items hosting a single or a small number of species. There were notable outliers in the two large floating Misawa docks and some of the JTMD vessels. Voyage duration was much longer for JTMD than any of the other

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[2] https://invasions.si.edu/nemesis/index.jsp

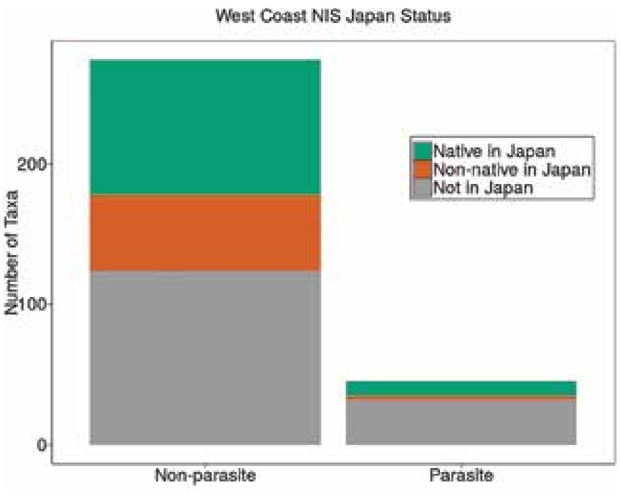

Figure 16-9. Total number of NIS reported for marine and estuarine habitats of Pacific North America. The figure indicates the number of NIS for invertebrates and algae (excluding vertebrates and vascular plants), for each free-living species and parasite/commensal species. Color coding indicates the number of NIS considered native to Japan (green), occurring in Japan as introduced (NIS) or cryptogenic (orange), or not reported to occur in Japan (gray). Data synthesis from NEMESIS (2003).

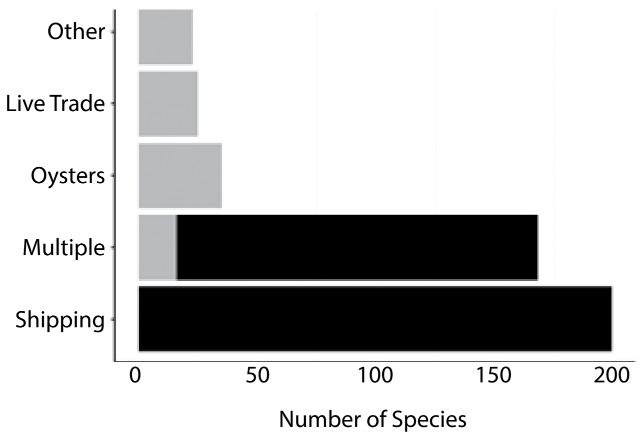

Figure 16-10. Vector strength for established NIS in North America. Shown are the numbers of NIS (invertebrates and algae) attributed to coarse vector categories through 2010, based on the initial introduction to North America; black bars indicate the number for which shipping is a sole or possible vector. "Multiple" refers to established NIS for which a single vector could not be definitively assigned. Figure adapted from Ruiz et al. (2015).

Table 16-6. Risk scores for each variable of the invasion process (source-transit-delivery) for JTMD and the other comparable vectors in the North Pacific.

	Source	Transit					Delivery	
Vector	**Source Pool**	**Richness per shipment**	**Number of shipments**	**Abundance per shipment**	**Voyage duration**	**Survival potential**	**Release to environment**	**Environmental match**
JTMD	H	L	H	NR	NR	M	H	M
Hull fouling	H	M	H	M	M	M	H	H
Ballast water	H	H	H	H	M	M	M	H
Ornamental	H	H	H	H	M	H	L	L
Aquaculture	H	L	M	H	M	H	H	H
Historical aquaculture	H	M	L	H	M	H	H	H
Historical ballast water	H	H	H	H	M	M	M	H

H = High, M = Medium, L = Low, NR = Not ranked

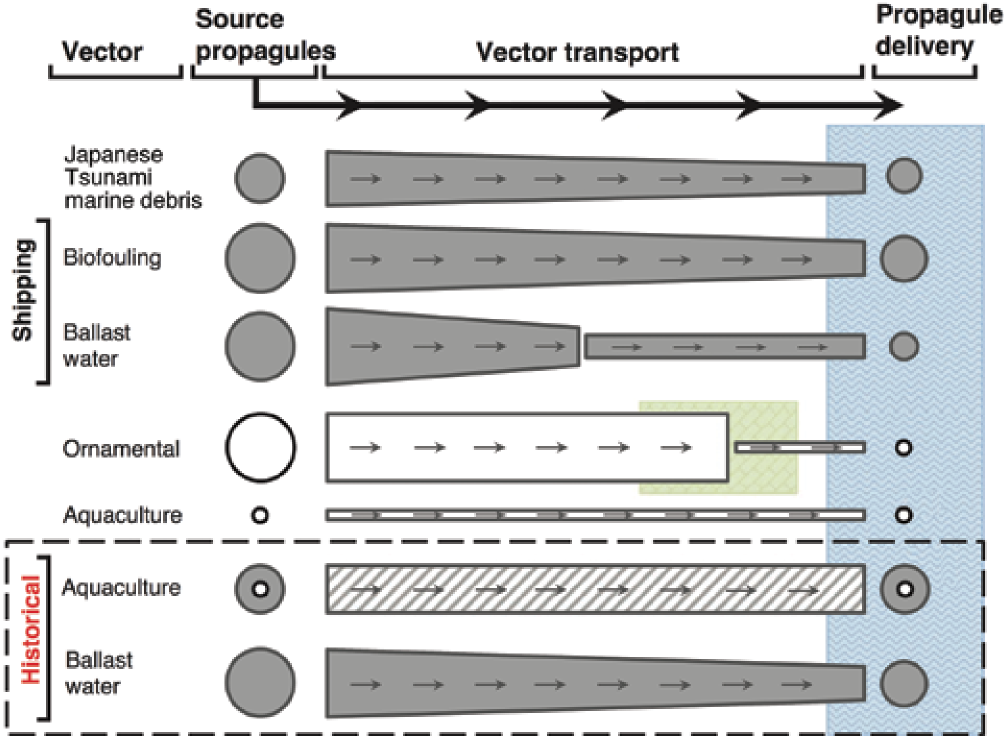

Figure 16-11. Comparison of Japanese Tsunami Marine Debris (JTMD) and six other maritime vectors. Eight vectors are compared across the relative size of the source propagule pools (the circles on the left), typical transit processes (the polygons in the middle section), and relative inocula sizes during propagule delivery (the circles on the right). The white circles and polygons represent target species pools and deliberate transfer activities during intentional vector processes; the gray solid circles and polygons represent unintentional transfers of species; the hatched polygons represent intentional transfers of species with associated unintentional transfers. The left-column circles' diameter represents the estimated species richness at the beginning of a typical transfer (the small, medium, and large circles reflect 1–9, 10–99, and 100–1000 species per shipment, respectively). Adapted from Williams et al., 2013.

vectors examined, with some items spending more than 6 years at sea, in comparison to a maximum of a few weeks in other vectors. The endurance of species associated with these extreme journeys is perhaps surprising given the conditions likely experienced in the open ocean.

Both ship fouling communities and ballast water differ from JTMD in that: (1) JTMD has a much slower at-sea transit speed (1–2 knots/1.9–3.7 km h^{-1}) versus typical commercial vessel speeds of 20 (37 km h^{-1}) or more knots, thus potentially affecting and impacting the development, adhesion, and retention of fouling communities, (2) JTMD has delivered communities of adult organisms, as compared to planktonic stages of benthic and fouling species in ballast water, and (3) JTMD typically involved arrival in shallow water, which allows extended periods of time for reproduction and colonization, as compared to biofouled vessels residing in port for a matter of only hours or days.

Remarkably, JTMD with living Japanese species from the Tohoku coast has continued to arrive on the Pacific coast North America and the Hawaiian Islands 6 years into the JTMD phenomenon. While plastic debris may last in the oceans for decades, it remains unclear what the long-term trajectory is for open-ocean survival of coastal species. Species recently detected arriving alive (as recently as May 2017) include the mussel *Mytilus galloprovincialis*, a suite of no fewer than 6 species of Japanese bryozoans, 2 species of yet-to-be-identified Asian sea anemones, 2 Japanese isopods (one, *Ianiropsis derjugini*, not previously detected), and other species.

From this comparison, we conclude that JTMD is most similar to hull fouling. No introductions have yet been detected in the surveys for JTMD species from Alaska to California and Hawaii. Many of the higher-risk species associated with JTMD have previously been introduced to at least one ecoregion in Pacific North America, and there is overlap with the species found associated with other vectors. Since a number of higher-risk species were found associated with JTMD, there is a potential for impacts to occur as a result of establishment events. While there remains the possibility of an introduction resulting from JTMD, higher-risk vectors like commercial hull fouling and ballast water continue to operate in Pacific North America, and any future introductions will be difficult to definitively assign to JTMD and rule out their introduction by these other means. Continued research and monitoring efforts in the affected ecoregions will build on the research conducted under the ADRIFT project and compare the role that JTMD played if a new introduction were to occur.

Acknowledgements

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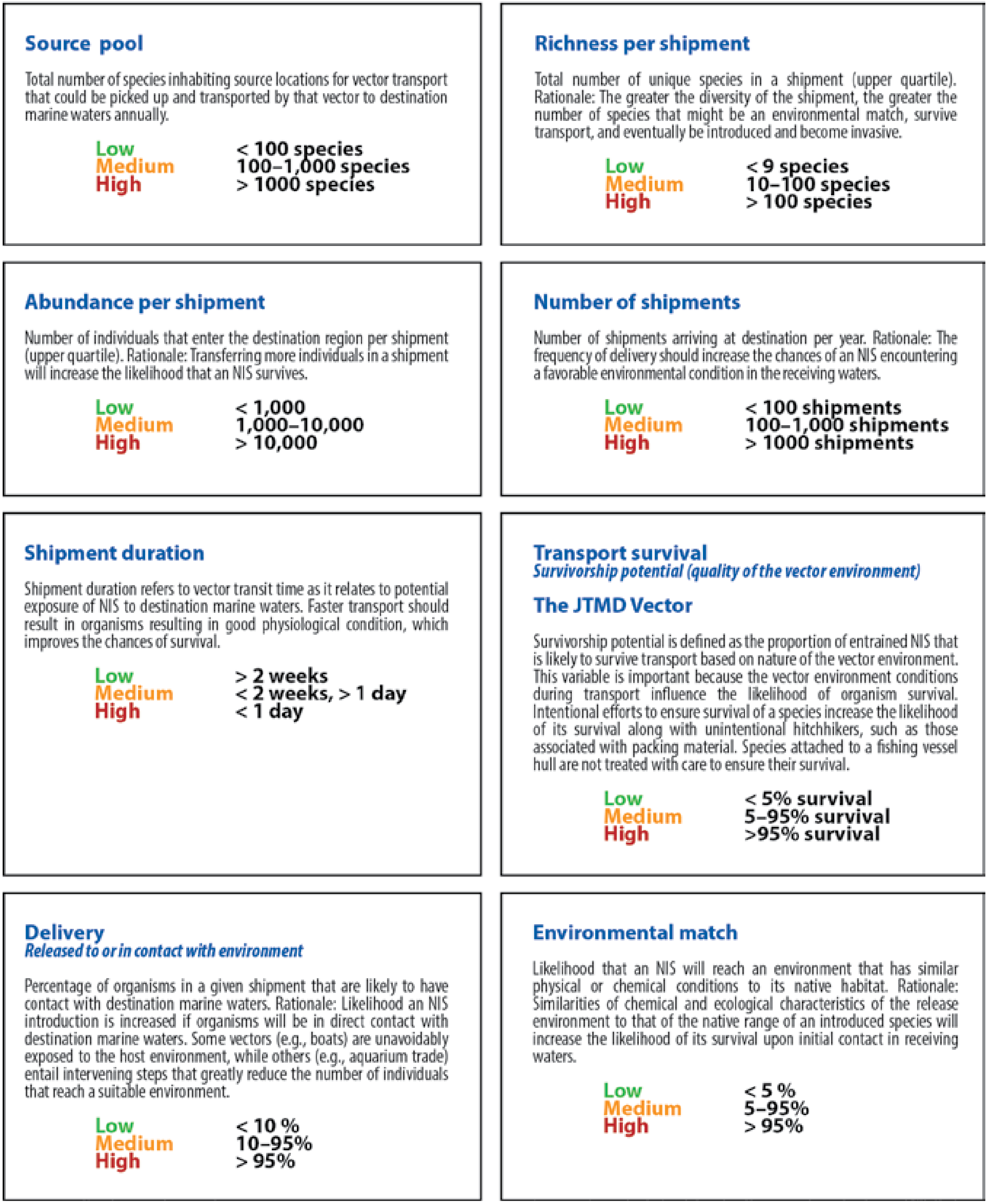
Chapter 16 Appendix

Appendix 16-1. Risk variable scoring definitions and rubric (adapted from COST, 2013)

Appendix 16-1. Risk variable scoring definitions and rubric (adapted from COST, 2013)



Source pool

Total number of species inhabiting source locations for vector transport that could be picked up and transported by that vector to destination marine waters annually.

Low	< 100 species
Medium	100–1,000 species
High	> 1000 species

Richness per shipment

Total number of unique species in a shipment (upper quartile). Rationale: The greater the diversity of the shipment, the greater the number of species that might be an environmental match, survive transport, and eventually be introduced and become invasive.

Low	< 9 species
Medium	10–100 species
High	> 100 species

Abundance per shipment

Number of individuals that enter the destination region per shipment (upper quartile). Rationale: Transferring more individuals in a shipment will increase the likelihood that an NIS survives.

Low	< 1,000
Medium	1,000–10,000
High	> 10,000

Number of shipments

Number of shipments arriving at destination per year. Rationale: The frequency of delivery should increase the chances of an NIS encountering a favorable environmental condition in the receiving waters.

Low	< 100 shipments
Medium	100–1,000 shipments
High	> 1000 shipments

Shipment duration

Shipment duration refers to vector transit time as it relates to potential exposure of NIS to destination marine waters. Faster transport should result in organisms resulting in good physiological condition, which improves the chances of survival.

Low	> 2 weeks
Medium	< 2 weeks, > 1 day
High	< 1 day

Transport survival

Survivorship potential (quality of the vector environment)

The JTMD Vector

Survivorship potential is defined as the proportion of entrained NIS that is likely to survive transport based on nature of the vector environment. This variable is important because the vector environment conditions during transport influence the likelihood of organism survival. Intentional efforts to ensure survival of a species increase the likelihood of its survival along with unintentional hitchhikers, such as those associated with packing material. Species attached to a fishing vessel hull are not treated with care to ensure their survival.

Low	< 5% survival
Medium	5–95% survival
High	>95% survival

Delivery

Released to or in contact with environment

Percentage of organisms in a given shipment that are likely to have contact with destination marine waters. Rationale: Likelihood an NIS introduction is increased if organisms will be in direct contact with destination marine waters. Some vectors (e.g., boats) are unavoidably exposed to the host environment, while others (e.g., aquarium trade) entail intervening steps that greatly reduce the number of individuals that reach a suitable environment.

Low	< 10 %
Medium	10–95%
High	> 95%

Environmental match

Likelihood that an NIS will reach an environment that has similar physical or chemical conditions to its native habitat. Rationale: Similarities of chemical and ecological characteristics of the release environment to that of the native range of an introduced species will increase the likelihood of its survival upon initial contact in receiving waters.

Low	< 5 %
Medium	5–95%
High	> 95%

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Chapter 17: Project summary and legacy products

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The Great East Japan Earthquake on March 11, 2011 was devastating for the people of Japan. In addition to the loss of life and coastal destruction, the ensuing tsunami inundated a significant portion of the northern coastal Tohoku region and created an unprecedented amount of marine debris that was jettisoned into the Pacific Ocean as a unique mega-pulse event. To assess and forecast the potential effects of this debris (termed Japanese Tsunami Marine Debris or JTMD), especially those related to non-indigenous species (NIS), on ecosystem structure and function, the coastlines, and communities along the Pacific coast of North America and the Hawaiian Islands (hereafter Hawaii), a 3-year PICES project (2014–2017), funded by the Ministry of the Environment of Japan (MoE), was developed and implemented. This project, referred to as ADRIFT (**A**ssessing the **D**ebris-**R**elated **I**mpact **F**rom the **T**sunami), brought together an international team of researchers from multiple scientific disciplines to focus on three main topics:

1. Modeling movement of marine debris in the North Pacific to forecast and hindcast JTMD trajectories and landings,
2. Surveillance and monitoring of JTMD landfall and accumulation, and
3. Characterizing and assessing the invasion risk of NIS transported on JTMD.

Key findings, publications and legacy products from this unique research project are summarized in this chapter.

To simulate the movement of JTMD and to forecast its propagation and destiny, large-scale oceanographic modeling was employed to highlight how the windage of different debris items affects their voyage duration and path. Model solutions suggest that light-weight floating debris (e.g., polystyrene materials) is transported rapidly, sometimes reaching Pacific North America within a year following the tsunami, while heavier partially submerged or sunken debris could remain in the ocean considerably longer, with the potential to become trapped in the part of the Subtropical Gyre known as the "garbage patch." Model predictions agree with the types of JTMD reported from different areas and timelines of its arrival on the Pacific North American and Hawaiian coasts, exhibiting strong seasonal and interannual variations. Additional model refinements allowed the evaluation of oceanographic conditions along probable paths of individual JTMD items, which was critical to better understanding the fate of NIS being carried on JTMD, thereby facilitating NIS risk assessments.

JTMD began arriving to coastal regions of Pacific North America and Hawaii within a year after the tsunami. The detection of indicator items at baseline marine debris monitoring sites suggested up to a 10-fold increase in the debris landings after 2013 over pre-tsunami levels. These observations are consistent with the spatial and temporal trends in disaster debris reports, shoreline debris surveys, and oceanographic modeling predictions, thus confirming a significant increase in debris influx on the Pacific coast of North America and in Hawaii. This debris influx differed by coastline, with low- to medium-windage JTMD washed ashore predominantly in Washington State, Oregon, Vancouver Island and the central coast of British Columbia, and higher-windage objects being landed mostly in northern British Columbia and Alaska.

In addition, systematic aerial photographic surveys were conducted to search for, and quantify, JTMD arriving on the coastlines of British Columbia and Hawaii. These surveys were the first comprehensive debris evaluations in these two regions, providing an important baseline of marine debris and complementing previous similar efforts in Alaska. An image analysis technique was developed to quantify marine debris abundance with high spatial resolution using archival aerial photographs.

JTMD carried living coastal Japanese organisms to the shorelines of Pacific North America and Hawaii. Since the summer of 2012, more than 370 species of algae, invertebrates and fish have been identified from over 630 intercepted and sampled JTMD items, with new species still arriving more than six years later (spring of 2017). In some cases, molecular techniques were needed to fully resolve species identity. A substantial number of these species rafting on JTMD, including many short-lived ones, were able to grow and reproduce during their multi-year journey through the relatively low-productivity open North Pacific Ocean habitat.

In addition to novel Japanese species carried by JTMD, some species that had been introduced previously to North America or Hawaii via traditional invasion vectors were redistributed by JTMD. Genetic analyses indicated that most JTMD macroalgae had haplotypes either identical, or very closely related, to populations in the Tohoku region that was affected by the tsunami, thus confirming both the source location for these potential invaders and ruling out secondary settlement from elsewhere in the North Pacific. The influx of new genetic material for many species may pose an additional risk to recipient ecosystems.

The invasion risk of species associated with JTMD was characterized using a screening-level risk assessment tool – the Canadian Marine Invasive Screening Tool (CMIST). Higher-risk invertebrate invaders were identified for each Pacific North American and Hawaiian ecoregion that received debris. Some of these species are well-known global invaders, such as the mussel *Mytilus galloprovincialis* and the ascidian *Didemnum vexillum*, which already have invasion histories in several of the assessed ecoregions. Others, like the sea star *Asterias amurensis* and the shore crab *Hemigrapsus sanguineus*, also are recognized global invaders but have yet to invade these ecoregions. Overall, risk varied by region, with the highest median risk given to northern California (an area that already hosts a number of NIS from historical vectors such as shellfish aquaculture and commercial shipping) and the highest cumulative risk given to Hawaii (an area that has the largest number of novel JTMD species because of its unique flora and fauna). A Top 10 Watch List for each ecoregion was produced. By synthesizing and investigating life history and tolerance traits for JTMD species, it was found that more than 30 relatively unknown Japanese species have traits similar to those with prior invasion histories, and may pose additional risks. Although detection surveys (fouling panel deployment, mussel parasite screening and visual inspections) carried out at more than 130 sites in each affected ecoregion in 2014–2016 have not identified any new invasions attributable to the tsunami, these surveys form an important record of the diversity that was present soon after the arrival of JTMD and can be used as baselines in the event of any possible future invasions. Given the lag-time often noted for marine invasions, monitoring efforts should be continued in all ecoregions.

Overall, there is little doubt that JTMD represents a novel transport vector for potentially invasive species to North America and Hawaii. As a vector, JTMD is most similar to hull fouling but given its unique, one-time nature, could be considered a lower risk when compared to other historical and contemporary ongoing vectors like commercial shipping, where the cumulative risk is substantially higher. Nevertheless, JTMD served to significantly raise global awareness of the potential role of marine debris in species dispersal.

The ADRIFT project produced a remarkable number of publications and legacy products. To date, key publications (all Open Access) include: a synthesis of the JTMD vector in *Science* (September 2017, Vol. 357, No. 6358, pp. 1402–1406)[1] and two journal special issues – one with papers focused on the taxonomy of JTMD species published in *Aquatic Invasions* (February 2018, Vol. 13, Is. 1, pp. 1–186)[2], and the other with papers on modeling, surveillance, monitoring, ecology and invasion risk of species published in *Marine Pollution Bulletin* (July 2018, Vol. 132, pp. 1–106)[3]. Two additional papers have since been published: one on the identification and invasion potential of marine algae arriving on JTMD by Hansen et al. in *Phycologia* (2018, Vol. 57, No. 6, pp. 641–658), and one on the establishment potential of tsunami debris associated species by Simkanin et al. in *Global Ecology and Biogeography* (2019, Vol. 28, No. 5, pp. 588–600).

Two special outreach products highlighting the project's purpose and findings for the general public are: an ADRIFT Factsheet – a colorful brochure (in English and in Japanese) distributed in printed form and through the PICES website[4], and an ADRIFT Videoscribe – a 4-minute narrated animation posted on YouTube[5].

The following are legacy products from the project available to the scientific community and public.

JTMD species database

The JTMD species database[6] on the Smithsonian Institution online portal NEMESIS (National Exotic Marine and Estuarine Species Information System) provides comprehensive information on the distribution, biology, ecology, life history traits and invasion history for selected species of marine invertebrates and algae from the northwestern Pacific Ocean, including those associated with JTMD that arrived to the coasts of North America and Hawaii. This information was compiled by applying a standardized search protocol of online resources and scientific literature written in both English and Japanese. The database is an important resource for improving our basic understanding of species transport and attributes related to invasion success, and can contribute to risk assessments.

JTMD specimen collections

Over 1,000 individual samples of marine invertebrates from more than 630 registered JTMD objects that landed on the Pacific coast of North America and Hawaii were placed for long-term stewardship at the Royal British Columbia Museum (RBCM, Victoria, Canada). Approximately 170 pressings of the larger marine algae from 42 registered JTMD objects and 30 smaller plastic debris items thought to also be from the tsunami, as well as 88 pressing of marine algae collected in the Tohoku region of Japan and similar to those found on JTMD, were deposited at the Oregon State University Herbarium (OSC, Corvallis, USA). These two archival specimen collections will allow researchers world-wide to access these unique resources now and in the years to come, especially with the undoubted advance of new analytical techniques. Additional funding for the JTMD marine invertebrate collection was provided by Fisheries and Oceans Canada through a grant from the Priorities and Partnership Fund to PICES.

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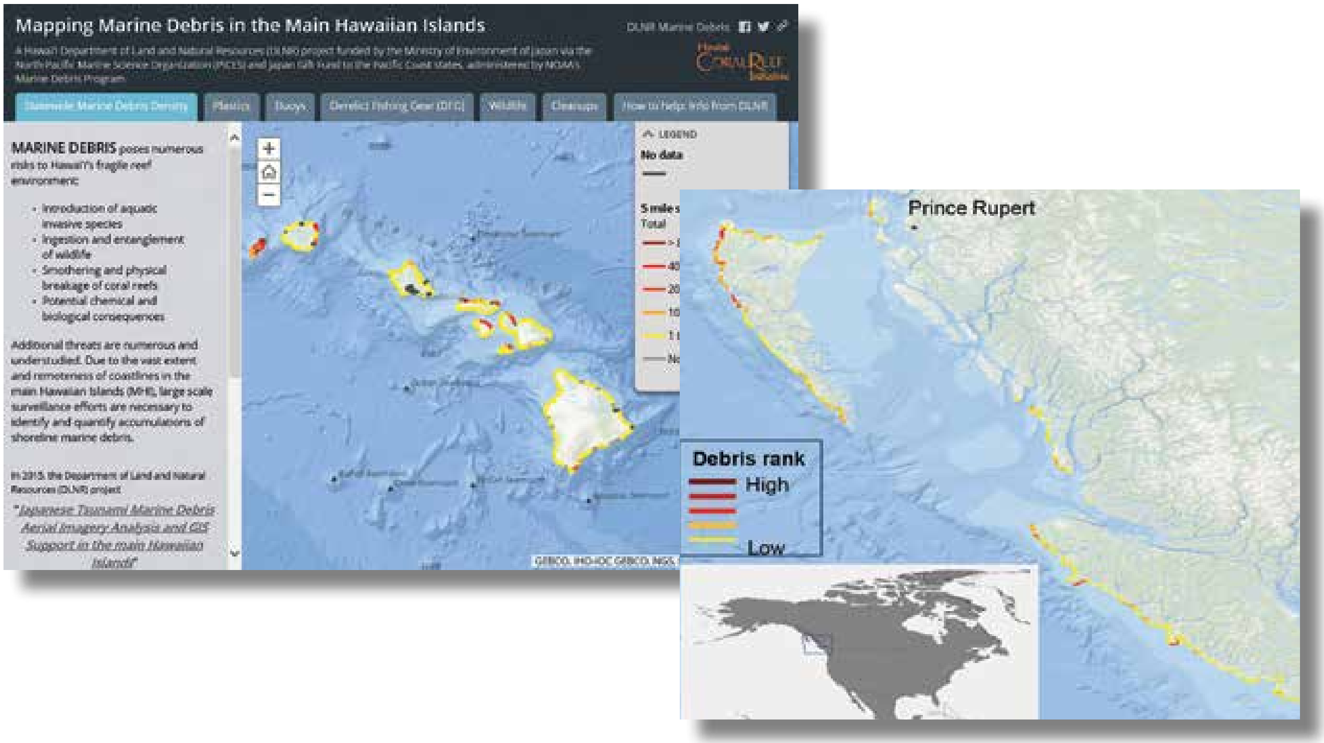
[1] https://science.sciencemag.org/content/357/6358/1402
[2] http://www.aquaticinvasions.net/2018/issue1.html
[3] https://www.sciencedirect.com/journal/marine-pollution-bulletin/vol/132/suppl/C
[4] https://meetings.pices.int/publications/other/ADRIFT-Factsheet-English.pdf
[5] https://www.youtube.com/watch?v=_OUCLMdyllU&feature=youtu.be
[6] http://invasions.si.edu/nemesis/jtmd/index.jsp

Samples of marine invertebrates that rafted across the Pacific Ocean on JTMD, preserved in ethanol at the Royal British Columbia Museum. Photo credit: Royal B.C. Museum



A Hawaii Department of Land and Natural Resources (DLNR) project funded by the Ministry of Environment of Japan via the North Pacific Marine Science Organization (PICES) and Japan Gift Fund to the Pacific Coast states, administered by NOAA's Marine Debris Program.

MARINE DEBRIS poses numerous risks to Hawaii's fragile reef environment:

- Introduction of aquatic invasive species
- Ingestion and entanglement of wildlife
- Smothering and physical breakage of coral reefs
- Potential chemical and biological consequences

Additional threats are numerous and understudied. Due to the vast extent and remoteness of coastlines in the main Hawaiian Islands (MHI), large scale surveillance efforts are necessary to identify and quantify accumulations of shoreline marine debris.

In 2015, the Department of Land and Natural Resources (DLNR) project

"*Japanese Tsunami Marine Debris Aerial Imagery Analysis and GIS Support in the main Hawaiian Islands*"

Density and distribution of debris on the coast of the main Hawaiian Islands and the outer coast of British Columbia.

British Columbia aerial survey mapping portal

In 2014 and 2015, the ADRIFT project funded aerial photographic surveys of the exposed outer coast (more than 1,500 km) of British Columbia (BC) to evaluate debris accumulation in this area. Additional funding for GIS analysis of the tagged photographs was provided by the Japan Tsunami Gift Fund, administered by the BC Ministry of Environment. All photographs, debris ranking segments and maps can be accessed through an online mapping portal designed and hosted by the BC Provincial Government (PICES Tsunami Debris Aerial Photo Survey)[7].

Hawaii aerial survey mapping portal

To identify and locate marine debris accumulation areas, aerial surveys of the eight main Hawaiian Islands (approximately 1,600 km of coastlines), coordinated by Hawaii's Department of Land and Natural Resources, were conducted between August and November 2015 to produce ortho-rectified photographs for analysis in GIS. This effort was funded by the ADRIFT project as well as by the Japan Tsunami Gift Fund to the Pacific Coast states, administered by NOAA's Marine Debris Program. All imagery and maps developed based on these surveys can be accessed through ArcGIS Story Map[8], and can also be viewed online or downloaded through the State of Hawaii Office of Planning Service Directory[9].

JTMD algae identification guides

An "*Identification guide of seaweeds on Japanese tsunami debris*" available on the Kobe University website[10], and morphological documentation on "*Benthic marine algae on Japanese tsunami marine debris*" accessible through Oregon State University's online library (Part 1: Introduction and the Brown Algae[11]; Part 2: The Green Algae and Cyanobacteria[12]; and Part 3: The Red Algae[13] have been prepared to assist the user in detecting JTMD algal species in the Eastern North Pacific.

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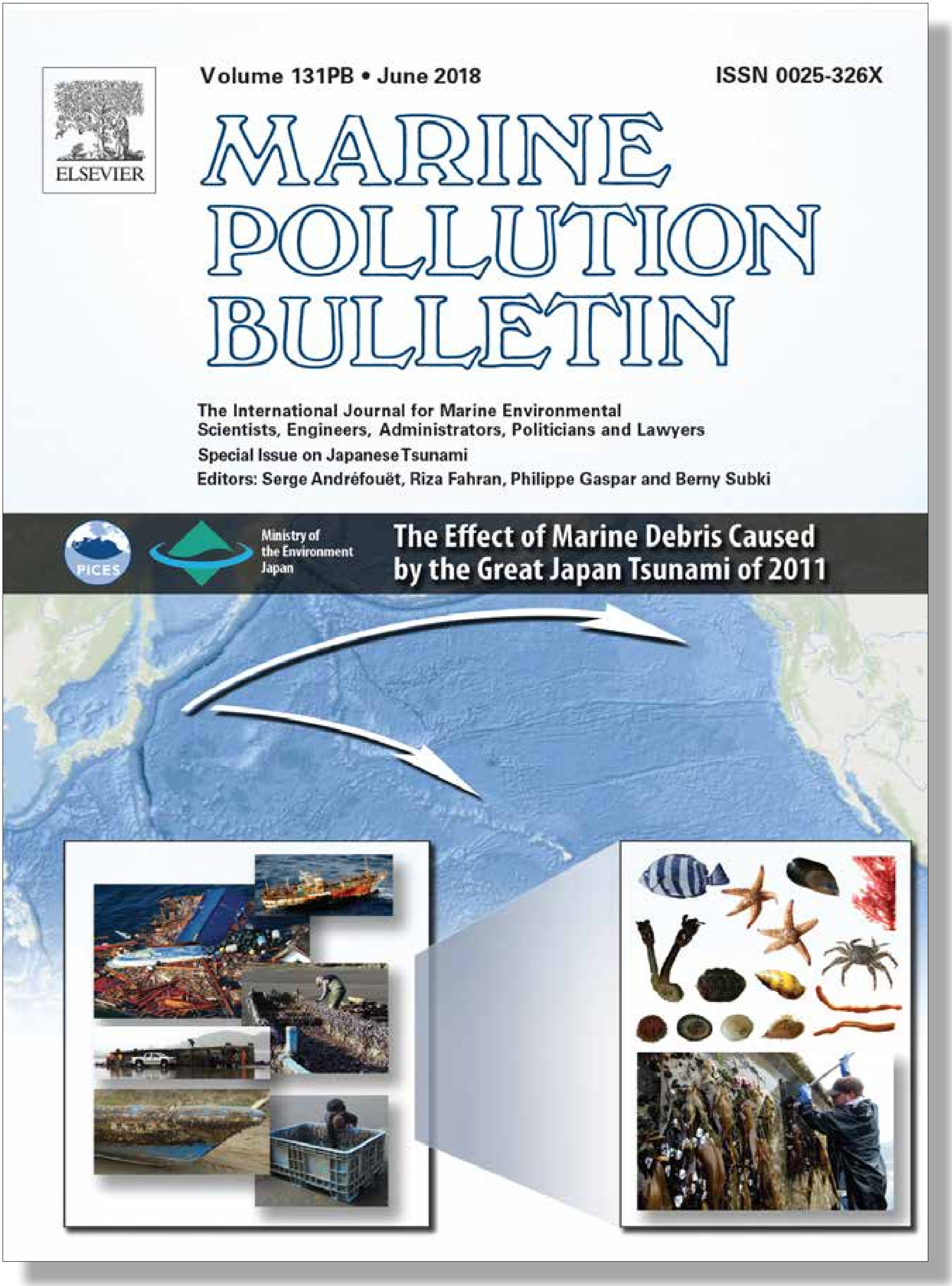
[7] http://catalogue.data.gov.bc.ca/dataset/pices-tsunami-debris-aerial-photo-survey-map
[8] http://arcg.is/29tjSqk
[9] http://geodata.hawaii.gov/arcgis/rest/services/SoH_Imagery/Coastal_2015/ImageServer

[10] http://www.research.kobe-u.ac.jp/rcis-kurcis/KURCIS/FieldGuide2017may14LR.pdf
[11] https://ir.library.oregonstate.edu/concern/defaults/cr56n576w
[12] https://ir.library.oregonstate.edu/concern/defaults/8049g9979
[13] https://ir.library.oregonstate.edu/concern/defaults/db78th95q



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MARINE POLLUTION BULLETIN

The International Journal for Marine Environmental Scientists, Engineers, Administrators, Politicians and Lawyers

Special Issue on Japanese Tsunami

Editors: Serge Andréfouët, Riza Fahran, Philippe Gaspar and Berny Subki

The Effect of Marine Debris Caused by the Great Japan Tsunami of 2011

U.S.Navy


Charles Moore

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