The Effects of Marine Debris Caused by the 2011 Tsunami

PICES
North Pacific Marine Science Organization
Report submitted to MoE
June 2017

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Executive Summary

The Great East Japan Earthquake on March 11, 2011 created a massive tsunami that washed millions of tons of debris into the Pacific Ocean. The overall goal of this PICES project, funded by the Ministry of the Environment of Japan (MoE), was to assess and forecast the 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 of the Pacific coast of North America and in Hawaii, 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 **T**sunami) focused on three main areas of research: (1) modeling movement of JTMD in the North Pacific, (2) surveillance and monitoring of JTMD landfall and accumulation, and (3) potential impacts from JTMD and associated NIS to coastal ecosystems in Pacific North America.

The modeling group utilized a suite of general circulation models to simulate movement of marine debris arising from the Great Tsunami of 2011. The team developed, refined, and calibrated these models using available observational reports to forecast the distribution of JTMD and timelines of its potential arrival on the Pacific Coast of North America and in Hawaii. These results illustrated how different types of JTMD were transported – light-weight and/or floating debris are transported rapidly and may be removed from the ocean within a year following the tsunami (*e.g.*, polystyrene), while heavy-weight and/or submerged/sunken debris can remain in the ocean considerably longer, with the potential to become entrained in the North Pacific gyre (*i.e.*, garbage patch). Simulated particles reaching the coasts of Washington and Oregon showed a strong seasonal cycle. The models were used to calculate probable trajectories of individual JTMD items to highlight areas where debris was likely to accumulate, as well as probable oceanographic conditions (temperature, salinity, and chlorophyll) along the JTMD trajectories to facilitate NIS risk assessments.

The surveillance and monitoring team characterized the temporal and spatial variability in JTMD landfall in North America and Hawaii and its relationship to the reported debris resulting from the Great Tsunami of 2011. Aerial photographic surveys were conducted for the main Hawaiian Islands and the outer coastline of British Columbia, Canada. Analysis of the monitoring data showed a sharp increase in the influx of debris items beginning in May 2012; indicator items, such as beverage containers and other consumer items, increased 10 times over records prior to the tsunami. A webcam system was installed at a site in Oregon during February 2015 to track beach-specific debris landings and removals to better understand temporal dynamics of debris on coastal beaches.

The NIS team characterized the invasion potential of species associated with JTMD by 1) documenting the biodiversity allied with arriving JTMD objects, 2) formally evaluating the risk of the species and JTMD as a vector for NIS overall, and 3) conducting detection surveys in Pacific

North America and Hawaii. Over the course of the project, 650 JTMD items have been intercepted and sampled, from which more than 380 species of algae, invertebrates and fish have been identified. With time, fewer species are arriving alive, but even as recently as spring 2017 live Japanese species were still documented arriving on JTMD objects in North America and Hawaii.

The risk of each species was formally evaluated, and lists of higher-risk species were generated for each Pacific North American and Hawaiian ecoregion (a biogeographic area with relatively homogenous species composition clearly distinct from adjacent systems due to similar oceanographic and topographic features) that received debris. Some of these species are well-known global invaders, such as the mussel *Mytilus galloprovincialis*, the ascidian *Didemnum vexillum*, the large pink barnacle *Megabalanus rosa*, and the seaweed *Undaria pinnatifida*. On average, the highest median risk was to Northern California, an area that already hosts a number of NIS from historical vectors like shellfish aquaculture and commercial shipping. Hawaii had the highest number of JTMD NIS that would be novel to the Hawaiian Islands. Detection surveys were carried out in each affected ecoregion: from Alaska to California, and Hawaii. Fouling panel deployment, mussel parasite screening and visual surveys were conducted in an effort to detect the establishment of invertebrate and algae species associated with JTMD. Thus far, surveys at more than 60 sites have not detected a single establishment event but serve as important baselines for future monitoring efforts as NIS introductions can take years to decades to detect. Perhaps the one exception is the striped beakfish *Oplegnathus fasciatus*, a Japanese species associated with JTMD which was observed independent from marine debris along the coast of Oregon and Washington, but we could not find evidence of an established population.

Based on this impressive body of research a number of conclusions can be drawn about the impact of marine debris from the Great Tsunami of 2011. A significant and substantial pulse of marine debris arrived on the shorelines of North America and Hawaii from 2012 to 2017 that can be directly attributed to this 2011 event. An unknown proportion 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 type of debris differs.

The biodiversity of Japanese coastal species associated with JTMD was varied and documented on recovered debris items. This has been the most intensely scrutinized group of species associated with a vector, with more than 65 taxonomists contributing to the identification effort. Overall, there is little doubt that JTMD may serve as a vector of potentially invasive species. However, when compared to other historical and contemporary vectors as mentioned above, JTMD is relatively low risk. JTMD represents a unique NIS vector compared to ongoing vectors like commercial shipping.

The ADRIFT project produced a remarkable number of publications and legacy products. Two journal special issues are in production (the expected publication date is late 2017); papers focused on the taxonomy of the JTMD species will be published in *Aquatic Invasions*, and papers on modeling, surveillance, monitoring, ecology and risk of species will be published in *Marine Pollution Bulletin*.

The following legacy products from the project are available to the public and scientific community: 1) the PICES JTMD species database on the Smithsonian Institution online portal NEMESIS (National Exotic Marine and Estuarine Species Information System), 2) the archival collection of specimens (marine invertebrates) from JTMD lodged at the Royal British Columbia Museum, 3) aerial photographs of more than 1,500 km of the exposed outer coast of British Columbia (BC), debris ranking segments and maps through the BC Provincial Government online mapping portal (PICES Tsunami Debris Aerial Photo Survey), 4) ortho-rectified aerial photographs of the eight main Hawaiian Islands and maps through ArcGIS Story Map, and through the State of Hawaii Office of Planning Service Directory, and 5) the field identification guide on NIS algae associated with JTMD at the Kobe University website; and morphological documentation on benthic marine algae found on JTMD through Oregon State University's online library; to be posted in July 2017.

プロジェクトの実施内容と成果の概要

2011年3月11日の東日本大震災で起きた巨大津波により、太平洋には数百万トンもの漂流物が流れ込んだ。環境省の拠出金による本PICES（北太平洋海洋科学機構）プロジェクトの全体目標は、この津波漂流物（JTMD：Japanese Tsunami Marine Debris（東日本大震災による洋上漂流物））、特に漂流物に生息していた非在来生物種（NIS: Non-Indigenous Species）が北米太平洋沿岸やハワイの生態系とその機能、沿岸部やコミュニティにもたらす影響を評価ならびに予測し、影響を緩和するための調査と管理手法を提案することであった。

ADRIFT（**A**ssessing the **D**ebris-**R**elated **I**mpact **F**rom **T**sunami: 東日本大震災起因海洋漂着物影響評価）と名付けられた本プロジェクトでは、(1) 北太平洋にある津波漂流物の挙動モデリング、(2) 津波漂流物の漂着と蓄積状況の観測とモニタリング、ならびに(3) 津波漂流物に係わる非在来種が北米太平洋の沿岸生態系にもたらす潜在的な影響調査の主に3つの研究分野に重点を置いた。

モデリンググループは、一般的な循環モデルを用いて、2011年の巨大津波で生じた洋上漂流物の動きをシミュレーションした。同グループは入手可能な漂流物の発見報告に基づいてモデルの開発、改良、校正を行い、津波漂流物の分布と北米太平洋岸やハワイへの漂着時期を予測した。これらの結果では、様々な種類の津波漂流物がそれぞれどのように漂流したかが示された。軽量の漂流物または浮遊する漂流物（ポリスチレンなど）はすぐに移動し、津波から1年以内に洋上から無くなる可能性がある一方で、重い漂流物、または沈下/半分以上に水中に浸かっている漂流物は洋上にかなり長期にわたって留まることがあり、北太平洋の大洋渦（いわゆるゴミベルト）に取り込まれる可能性があることが示された。シミュレーション上でワシントン州やオレゴン州の沿岸に漂着するとされた粒子は、はっきりした季節的な周期を有することが示された。このモデルは、個々の津波漂流物の考えられる漂流経路を計算することにより漂着物が畜積しやすい場所を見つけ出すと共に、津波漂流物が通過した海域の水温、塩分、クロロフィルといった想定される海洋学的な状態も推定し、非在来種のリスク評価を進めるために用いられた。

観測とモニタリングのチームは、北米とハワイにおける津波漂流物の漂着に時空間的な変動について検討し、2011年の巨大津波による漂流物であると報告されたものとの関係性を示した。ハワイの主要な島々とカナダのブリティッシュコロンビア州の縁辺沿岸線の空中写真撮影を行った。モニタリングデータの分析によると、2012年5月初旬に漂流物漂着の急激な増加がみられており、飲料水容器やその他の消費財などの指標物は津波発生前の記録の10倍増となった。海岸ごとに特異的な漂流物の漂着と再流出状況を追跡し、沿岸部海岸における漂流物の経時的な挙動を詳細に把握するため、2015年2月にオレゴン州のある場所にウェブカメラシステムを設置した。

非在来種チームは、津波漂流物に係わる種の侵入の可能性について、1)漂着した津波漂流物に係わる生物多様性（種類）のリスト作成、2) 生物種のリスクの公式的な評価と非在来種の運び屋としての津波漂流物の包括的な評価、ならびに 3)北米太平洋岸とハワイにおける非在

来種の調査により検討した。本プロジェクトの実施を通じて、650 個の津波漂流物が捕捉、採取されたが、その中から 380 種以上の海藻、無脊椎動物や魚が特定された。時間とともに、生きたまま漂着する種は減っているが、2017 年春になっても北米とハワイで津波漂流物に付着した日本の種の漂着が記録されている。

各生物種のリスクは公式な手法で評価され、漂流物が到着した北米太平洋岸やハワイのそれぞれの生態区分（相似した海洋学的・地理的な特性により, 隣接する生態系とは区別される比較的均一な生物種組成を有する生物地理区）ごとに、より高リスクの生物種のリストが作成された。これらの種の一部は、ムラサキガイ（*Mytilus galloprovincialis*）、ホヤ（*Didemnum vexillum*）、アカフジツボ（*Megabalanus rosa*）、ならびにワカメ（*Undaria pinnatifida*）といった世界的な侵入種としてよく知られているものである。中間リスクが最大となるのは、すでに貝の養殖や商船輸送などの従来の運び屋から多くの非在来種を迎え入れている北カリフォルニアであった。ハワイでは、ハワイの島々でこれまでに観られなかった非在来種について、最も多い種類数が津波漂流物から見つかっている。非在来種を見付けるための現場調査は、アラスカ州、カルフォルニア州からハワイ州に至るまで津波漂流物が漂着した各生態区分で行われた。付着生物捕集用のパネルの設置、ムラサキガイへの寄生生物選別と、津波漂流物に係わる無脊椎動物と海藻類の定着を確認するための目視調査が行われた。これまで 60 か所以上で行われた調査では、津波漂流物に係わる非在来種の定着を示すケースはまったく観られなかったが、非在来種の移入は見付かるまで数十年かかることもあるため、今後のモニタリングを行う上での重要な基本データとなった。おそらく、津波漂流物から見付かった日本の生物種であるイシダイ（*Oplegnathus fasciatus*）は例外の 1 つで、オレゴン州とワシントン州の沿岸部沿いの海洋漂流物とは別の所で生息していることが観察されたが、個体群が定着した証拠は見つからなかった。

以上の目覚ましい研究活動に基づき、2011 年の巨大津波による洋上漂流物の影響について数多くの結論を導くことができる。2011 年の巨大津波に直接起因すると考えられた、おびただしい量の洋上漂流物が 2012 年から 2017 年までに北米やハワイの沿岸部に周期的に漂着した。その割合は不明であるが津波漂流物は北太平洋を浮遊したままであり、今後数年間にわたって漂着し続ける可能性がある。漂流物の種類は異なるが、この震災起因の漂流物の元々の量は、震災以外の起源から海洋に一年単位で流れ込んでいるのと同等の規模である。

津波漂流物に係わる日本の沿岸部の種の生物種は多岐にわたり、回収された漂流物ごとに記録されている。これは、種の特定に 65 人以上の分類学者が関与した、1つの運び屋に係わる種群について最も集中して精査されたケースとなっている。全体的にみて、津波漂流物はおそらく潜在的な侵入種の運び屋としての役割を果たすであろうことに疑いの余地はない。しかし、その他の前述したような従来と現在の運び屋と比較すると、津波漂流物は比較的リスクが低い。津波漂流物は、商船輸送などの継続して運行されている運び屋と比較して、非在来種の独特の運び屋の典型である。

ADRIFT プロジェクトは、数多くの出版物と遺産（レガシー）を生み出した。2 つの学術誌で特別号が作成中であり（2017 年後期に発刊予定）、津波漂流物に係わる生物種の分類学に焦点を

絞った論文は『Aquatic Invasions』誌に、モデリング、観測、モニタリング、生態学ならびに種のリスクに関する論文は『Marine Pollution Bulletin』誌に、それぞれ発表される予定である。他に本プロジェクトから生み出された以下のような成果（レガシー）が利用出来る。1）スミソニアン協会オンラインポータルサイト NEMESIS（National Exotic Marine and Estuarine Species Information System: http://invasions.si.edu/nemesis/jtmd/index.jsp「海洋と河口域における外来種に係わる国立情報システム」）にある PICES 津波漂流物に係わる種を収集したデータベース、2）ロイヤルブリティッシュコロンビア博物館にある津波漂流物から収集された生物標本（無脊椎動物）の収集保管物、3）ブリティッシュコロンビア州政府よりオンライン入手可能な同州の海岸総延長 1,500 km 以上におよぶ外縁沿岸部の空中写真と漂着物蓄積度合いを区分けしたオンライン地図ポータルサイト (http://www.arcgis.com/home/webmap/viewer.html?webmap=3c5fb88b7f3f4d97974615acad67af3e、4）幾何補正されたハワイの8つの主要な島々の空中写真と ArcGIS ストーリーマップ (http://arcg.is/29tjSqk)とハワイ州計画サーヴィスによる web 地図（http://geodata.hawaii.gov/arcgis/rest/services/SoH_Imagery/Coastal_2015/ImageServer)、5）津波漂流物に係わる非在来種の海藻同定用の一般市民ならびに研究者向けの神戸大学による野外ガイド（http://www.research.kobe-u.ac.jp/rcis-kurcis/KURCIS/FieldGuide2017may14LR.pdf）と、オレゴン州立大学のオンライン・ライブラリー (https://ir.library.oregonstate.edu/); 2017 年 6 月掲載予定）を通じて閲覧可能な津波漂流物に係わる底生（付着性）海藻に関する記載である。

Chapter 1: Introduction

The devastating Great Tsunami of 2011 created an unprecedented amount of marine debris, which has the potential to remain floating in the ocean for a very long time. After the Japan tsunami, marine debris (hereafter JTMD) started arriving on the shores of the Pacific coast of North America and later in Hawaii, amazing discoveries were made: numerous species were found on two large Misawa docks, an increasing number of skiffs, as well as smaller and diversified objects, including objects originating from on land.

What makes JTMD different?

Two enduring 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", and (2) How does marine debris rafting, 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"? Historic rafting largely consisted of biodegradable materials such trees, tree branches, and root masses. We know little 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, while not impossible, suggests that such events are likely rare. The biodeterioration and decomposition of post-and-beam wood in about a 2-year period, as observed in this study, suggests 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, suggests 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.


Photo credit: Lightspeed Digital

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? We note that JTMD differs from the modern transport of marine life in both ship fouling communities and in ballast water by (1) JTMD having a much slower at-sea transit speed (1-2 knots) *versus* typical commercial vessel speeds of 20 or more knots, thus potentially affecting and impacting the development, adhesion, and retention of fouling communities; (2) JTMD has delivered extensive communities of adult organisms, as compared to planktonic stages of benthic and fouling species in ballast water, (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, as compared to biofouled vessels residing in port for only hours or days. Through this project, we quantified the reach and impacts of JTMD, and compare JTMD as a vector of non-native species to other known vectors, such as the historical transport of Pacific oysters from Japan to North America and Hawaii, commercial ship fouling and ballast water communities.

Identification of objects as Japanese Tsunami Marine Debris

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, which data could then be provided to the Japanese Consulate.
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 bear 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 occasional over layering 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 and on, and characterized by subsequent slowing in item arrivals as the debris field entered its 4th, 5th, and 6th years. If debris were arriving independently and steadily 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 -- since 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 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. **Vessels:** Finally, 100% of all objects -- vessels or otherwise -- intercepted in Hawaii or North America since 2012, thought to be from Japan and that 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.


Photo credit: US Navy

Project overview

The overall goal of this PICES project, funded by the Ministry of the Environment of Japan (MoE), was to assess and forecast the effects of debris generated by the Great Tsunami of 2011 and suggest necessary measures for mitigation. To achieve this, the project investigated potential impacts to the coastlines and communities of the Pacific coast of North America and Hawaii, including impacts on ecosystem structure and function, with emphasis on those related to the effects of non-indigenous species.

The project spanned three years, from April 15, 2014 to March 31, 2017. The project was directed by a Project Science Team (PST), co-chaired by three PICES members, one each from Canada (Dr. Thomas Therriault), Japan (Dr. Hideaki Maki) and the USA (Ms. Nancy Wallace). All PST members are listed in Chapter 19. The PST Co-Chairmen were responsible for reporting annually to MoE and PICES Science Board on the scientific implementation of the project. This report should be submitted to MoE within 90 days after the close of each project year ending March 31, and include a summary of the activities carried out over the entire span of the project. The Project Coordinator, Dr. Alexander Bychkov, is responsible for the management of the fund and for reporting annually on its disposition to MoE and PICES Governing Council within 90 days after the close of each project year ending March 31. We intend to host two symposia in Japan during late spring 2017 to disseminate project results.

The project focused on three main areas of research modeling movement of marine debris in the North Pacific, surveillance and monitoring of tsunami-generated marine debris landfall, and risk (including potential impacts) from potentially invasive species to coastal ecosystems. The report is divided into six THEMEs: (1) movement of debris – Chapter 2, (2) arrival of debris – Chapters 3-6, (3) rafting of Japanese species – Chapters7-10, (4) characteristics of JTMD species – Chapters 11-12, (5) detection of invasion – Chapters 13-14, and (6) risk of invasion – Chapters 15-16. A more detailed description of the project's research activities and findings is available in the following Chapters and the full submitted reports for each funded activity are attached as Appendices.

Photo credit: Hideaki Maki

THEME I – Movement of Debris

Chapter 2: Modeling oceanographic drift of Japanese Tsunami Marine Debris

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Abstract

To model the movement of Japan tsunami marine debris (JTMD) items and the accompanying environmental conditions that the associated biota would have experienced during the journey, the project used three numerical models: Surface CUrrents from Diagnostic (SCUD) model operated at International Pacific Research Center (IPRC) of 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 National Oceanic and Atmospheric Administration (NOAA), and MOVE/K-7/SEA-GEARN system operated by the Meteorological Research Institute (MRI)/ Japan Agency for Marine-Earth Science and Technology (JAMSTEC)/Japan Aerospace eXploration Agency (JAXA) group. 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 demonstrated 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

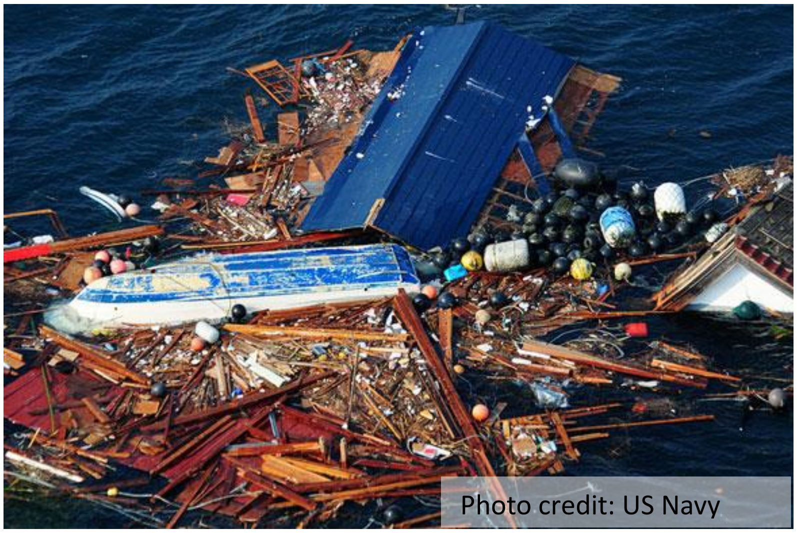
Photo credit: US Navy

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 1000 boats were washed into the ocean by the tsunami, of which 300-500 may still be floating.

Model results combined with statistics of satellite temperature observations were used to demonstrate that conditions along the Pacific coast of North American and in Hawaii were within the range of that along the eastern shores of Japan. New methods and approaches developed by the 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 allowed 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 trajectories that will facilitate assessment of possible survival of coastal species during their trans-Pacific travel.

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 system 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 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 the following:

- 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 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 (Assessing the Debris-Related Impact From Tsunami) project, the modeling team developed a set of new methods and enhanced existing techniques. The accuracy of the modeling results has been verified through their comparison with available observations and in sensitivity studies, conducted using three different models and different setups for numerical experiments.

SCUD Model

The *SCUD model* (Surface CUrrents from Diagnostic) was developed at the IPRC (International Pacific Research Center), 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) 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).


Photo credit: NOAA

MOVE/K-7/SEA_GEARN Model

The MOVE/K-7/SEA-GEARN drift/dispersion model was created by a team of scientists in Japan from JAMSTEC, Japan Atomic Energy Agency (JAEA), MRI, and JAXA in order to examine the debris positions in the North Pacific, landing positions, and landing dates on the coast after the

Great East Japan Earthquake and Tsunami occurred on March 11, 2011. Model simulations that provided velocity product 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 (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 have been focused on producing a "hindcast" model run, which simulates the movement of tsunami debris from March 11, 2011 through the present. The debris is 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° operational HYCOM from Naval Research Laboratory (HYCOM 2016) and 0.25° global NOAA Blended Sea Winds (NOAA 2016). Unlike other models, GNOME also accounts for such coastal processes as re-floatation of debris, temporarily washed ashore.

Model analysis and comparison

Modeling studies on this 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 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 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 North American Pacific 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 travel of Japanese coastal species to ecoregions in North America and Hawaii with JTMD.

Results and Discussion

Source information

The tragic Great Tsunami of 2011 was a disaster that devastated many towns and villages and changed the appearance of a significant stretch of the coastline of the 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 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 Asahi Shimbun, which we received through a personal communication with Dr. Maki. Figure 2-1a shows the distribution of reports along the shoreline and reveals that the highest number of affected homes was located between 37.5N and 39.8N. Our analysis of the overlaps between the two sources of the data confirmed a good agreement between them, so for towns where two estimates were available we used an average number. In other regions, municipal and Asahi data were used to complement each other (Figure 2-1b). To convert the discrete source data into a continuous function, a set of parameters were 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 has not changed the main conclusions of our study, some details of model fluxes on the North American and Hawaiian coastlines were sensitive to the spatial distribution of sources.

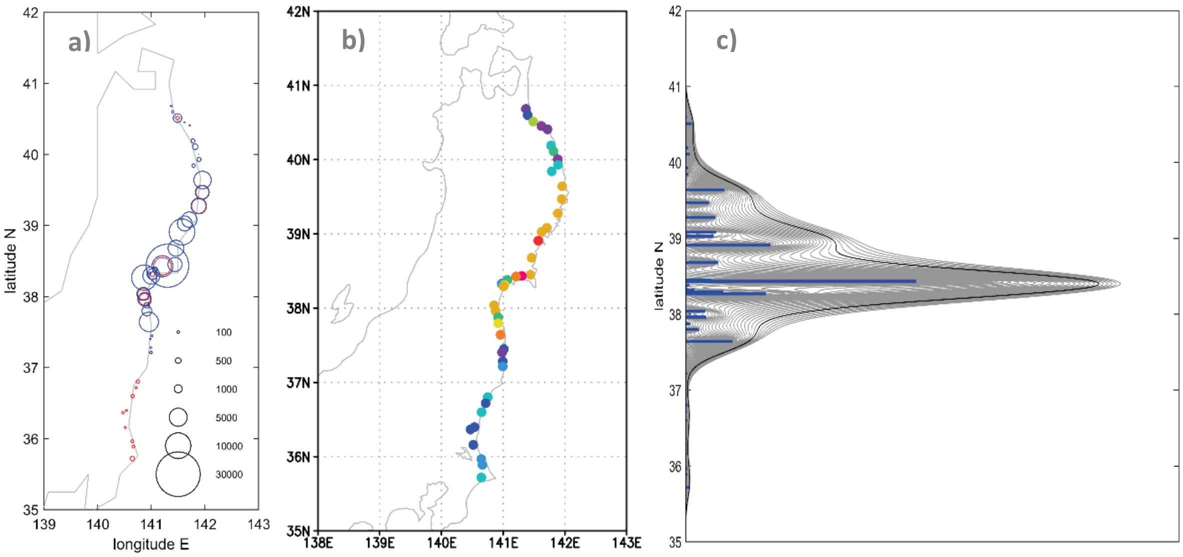

Figure 2-1. a) Number of affected homes, reported by municipal sources (blue) and Asahi Shimbun (red). b) Composite data distribution. c) 'Source function' of JTMD calculated with a variety of filters and used to initiate model simulations.

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, Kuroshio Extension with a well-developed first meander around 143E, subpolar front around 40N, and a very strong anticyclonic eddy centered approximately at 39N, 143.5E. The latter eddy may have played a very important role in the JTMD drift in March 2011. Frequently there is a branch of 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 by the Kuroshio Extension and advected east. This structure corresponded well with reports from the Japan Coast Guard who reported March 20-21, 2011 smaller off-shore extent of the debris field between 37 and 38N than north and south of these latitudes. Particle simulations with GNOME were difficult to compare with tracers in other models. A model source from eight 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.

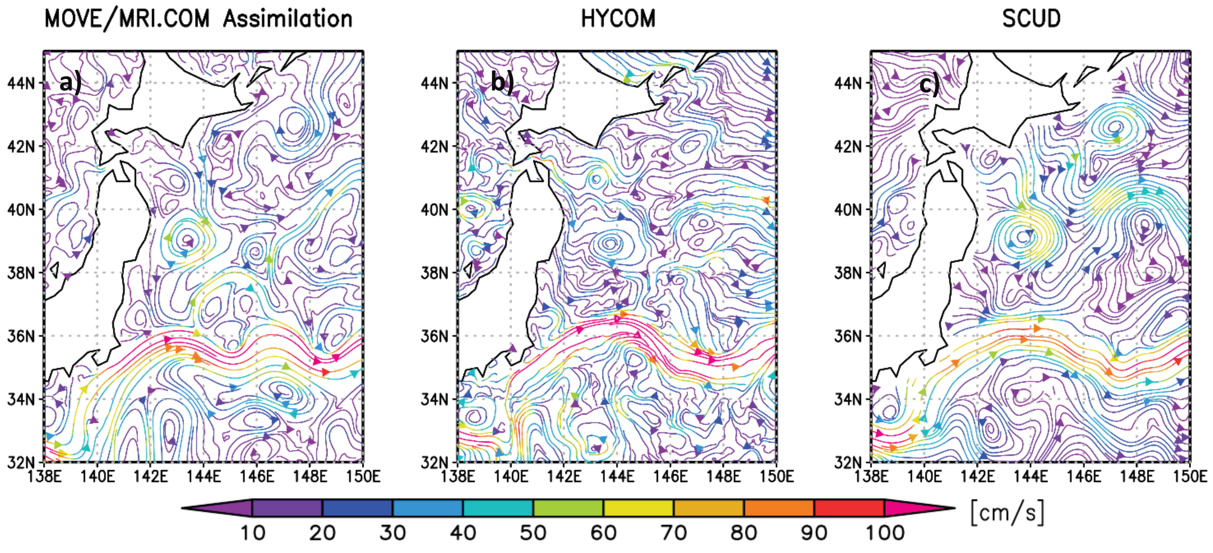

Figure 2-2. Streamlines of surface currents in (a) MOVE/K-7/SEA-GEARN, (b) HYCOM, and (c) SCUD models for March 11, 2011. Colors represent current speed and units are cm/s.

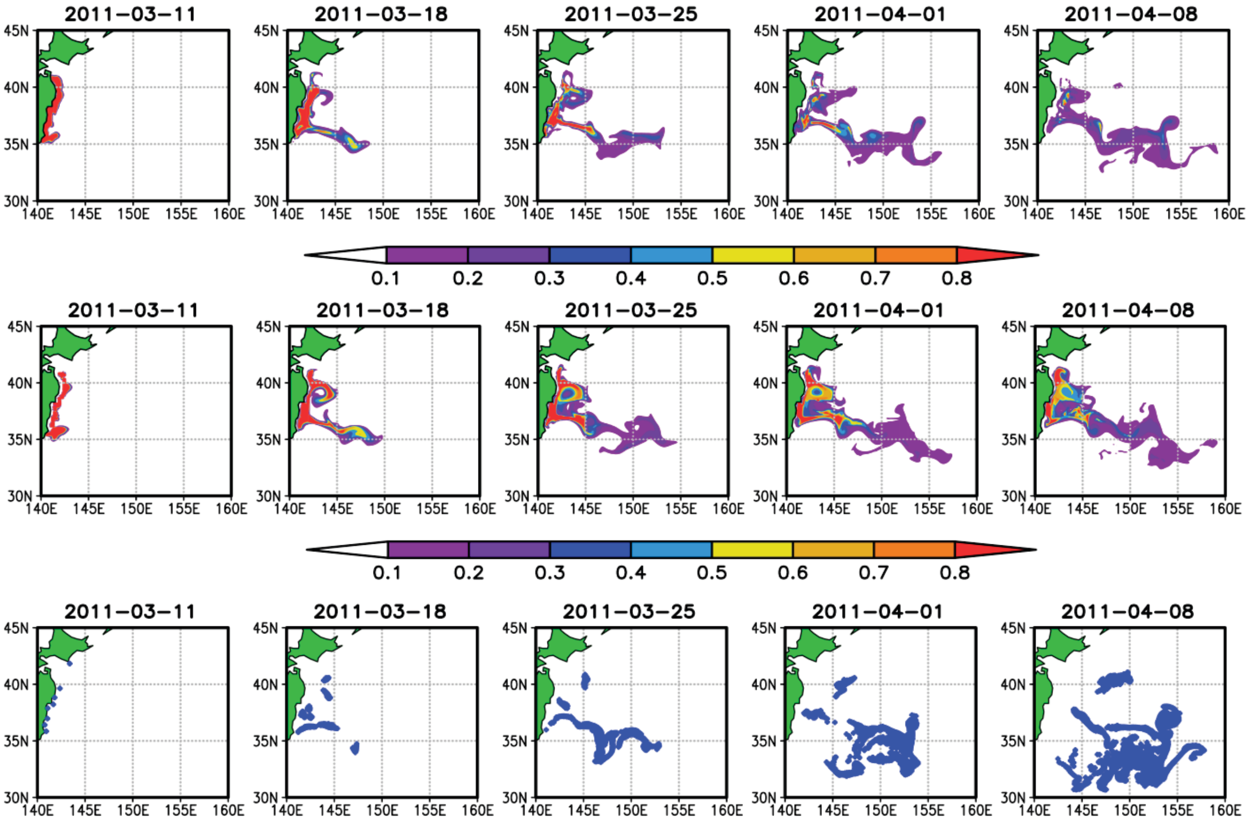

Figure 2-3. Tracer concentration for SCUD (top row), MOVE/K-7/SEA-GEARN (middle row) and particle locations in GNOME (bottom) models for windage parameter 1.5% on March 11, 2011 and 1, 2, 3, and 4 weeks later.

High-resolution in coastal areas

High model resolution was important for adequate simulations of debris drift in coastal areas, where dynamical scales were 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 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: (i) the new model grid is a 10-km HYCOM grid, (ii) data > 200 km from shore are interpolated SCUD data, (iii) data < 100 km from shore are unbiased HYCOM data, and (iv) 100-200km 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.

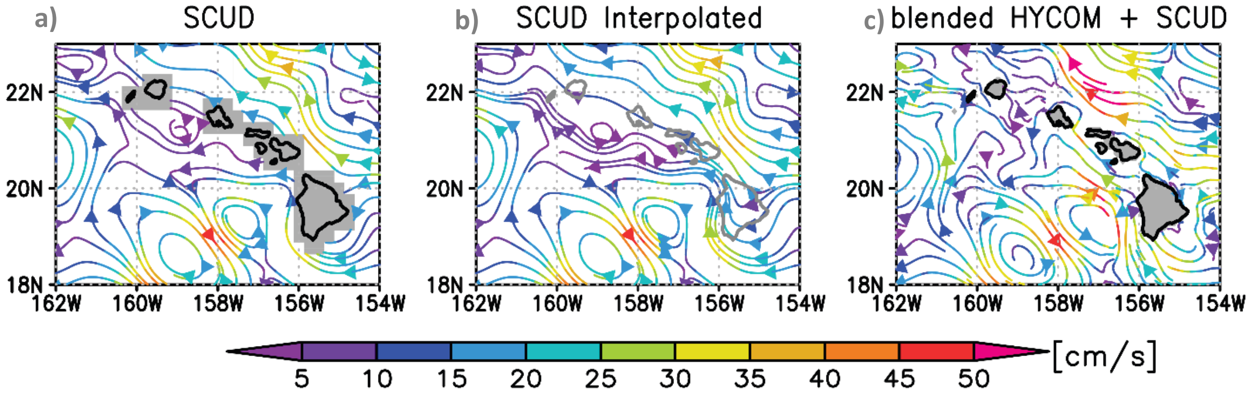

Figure 2-4. Streamlines of surface currents around Hawaii for March 11, 2011 in (a) the original ¼-degree SCUD model (gray shows model land mask), (b) SCUD model interpolated over Hawaiian Islands, and (c) SCUD model blended with HYCOM data on a 10 km grid. Colors represent current speed and units are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

Multi-windage modeling based on particle/tracer simulations

Ocean models describe 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 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-) and MOVE/K-7/SEA-GEARN (Figure 2) models were used to calculate tracer density evolution and GNOME (Figure 2) operated with a large number of particles.

Even without further analysis, Figures 2-5 to 2-7 provide 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 North American Pacific 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, 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 two other models. Also, after August 31, 2013 the MOVE/K-7/SEA-GEARN model switches into a forecast mode that resulted in some loss of accuracy, especially in the eastern North Pacific, where model resolution was degraded to ½-degree.

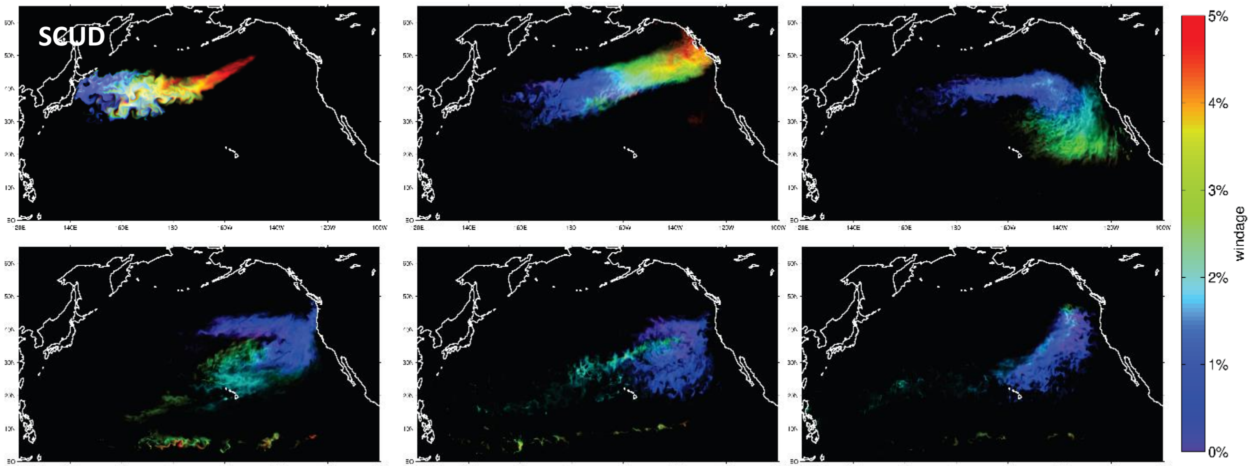

Figure 2-5. Evolution of JTMD tracer in the SCUD model simulations. Colors indicate windage of the debris. From top left to bottom right: September 1, 2011, March 1, 2012, September 1, 2012, March 1, 2013, September 1, 2013, and March 1, 2014.

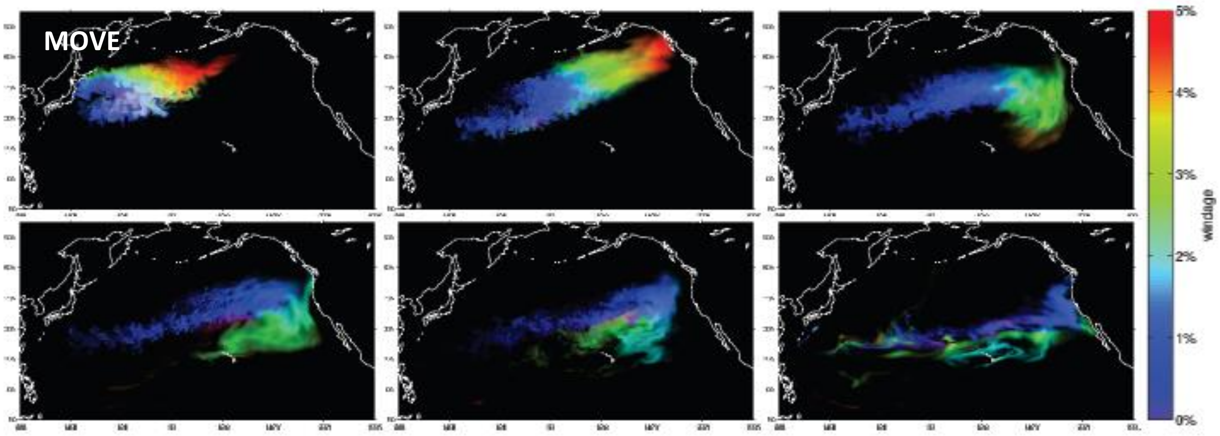

Figure 2-6. Evolution of JTMD tracer in the MOVE/K-7/SEA-GEARN model simulations. Colors indicate windage of the debris. From top left to bottom right: September 1, 2011, March 1, 2012, September 1, 2012, March 1, 2013, September 1, 2013, and March 1, 2014.

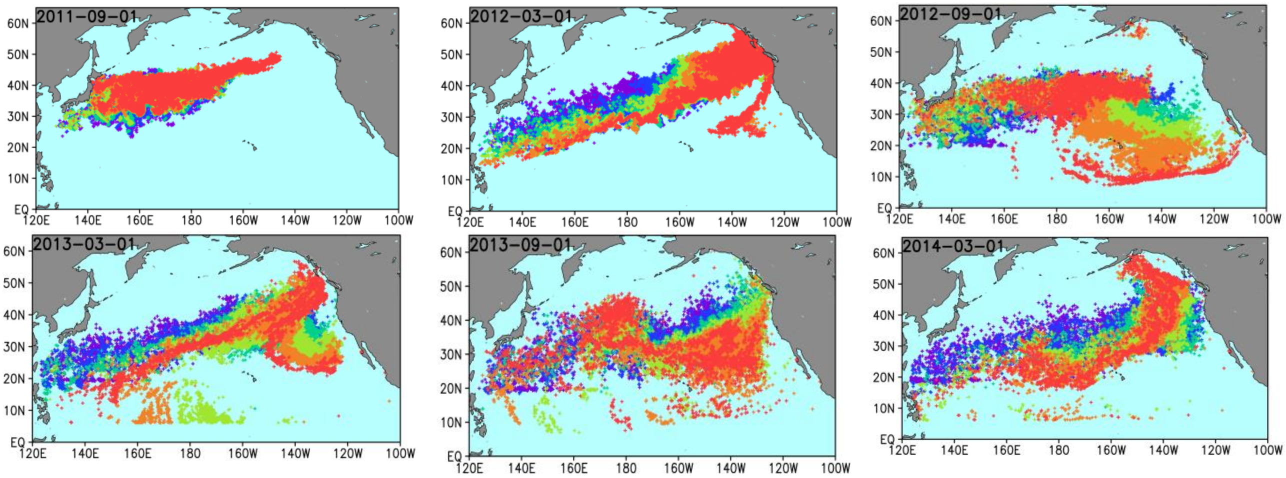

Figure 2-7. Evolution of particle locations in the GNOME model simulations. Colors indicate particle windages according to the color scales of Figs. 2-5 and 2-6. High windages are plotted on top of lower windages. From top left to bottom right: September 1, 2011, March 1, 2012, September 1, 2012, March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

Model comparison with observational reports in North America

Overall, observations of marine debris are very sparse and make 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 North American Pacific coast were unique in a sense that (i) there was a high probability of them being noticed and reported and (ii) 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.

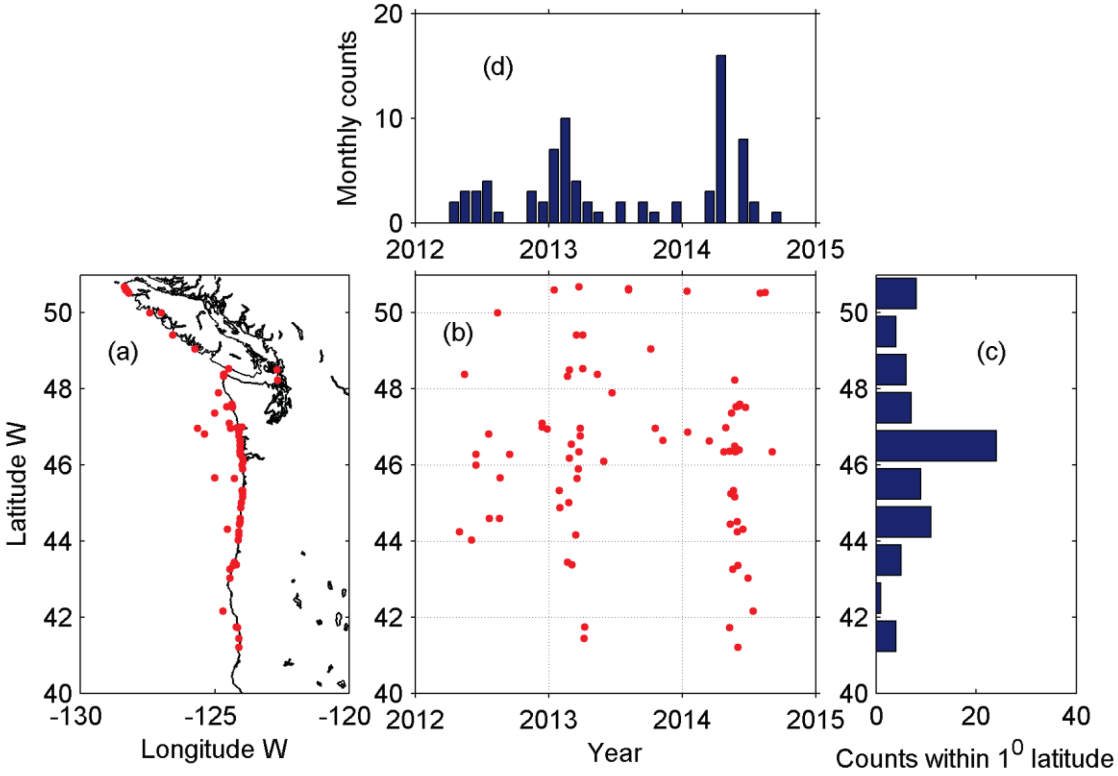

Figure 2-8. Reports of JTMD boats from the US/Canada coastline between 40 and 51N. (a) Location of reports relative to the shoreline. (b) Latitude-time diagram. (c) Number of reports in 1-degree latitude bins. (d) Monthly number of reports.

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 SCUD 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 in Figure 10) and GNOME (green GNOME 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 lead observations by 3-4 months and the magnitude of the second peak was severely underestimated. Low magnitude of the 2nd 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.

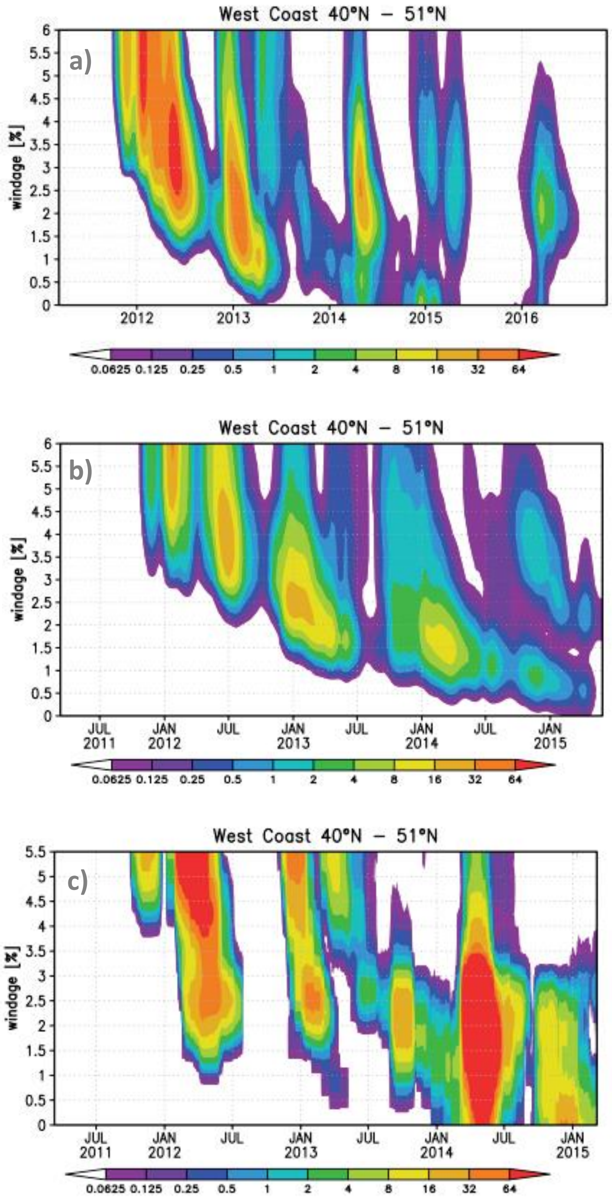

Figure 2-9. Model fluxes timelines on the North American west coast for different windages, calculated from a) SCUD, b) MOVE/K-7/SEA-GEARN, and c) GNOME. Units are conventional and differ between the panels.

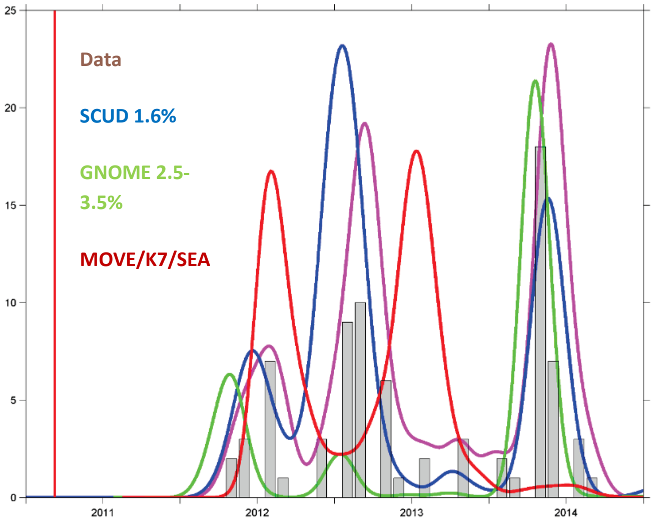

Figure 2-10. Monthly counts of boats on the U.S./Canada west coast (gray bars) and low-pass filtered timelines of boat fluxes in observations (magenta) and model experiments with different windages: 1.6% for SCUD (blue) and 2.5–3.5% averages for GNOME (green) and MOVE-K7/ SEA-GEARN (red). Vertical red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

Scaled and projected back to the start point, the SCUD model estimates 1000 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 (Ministry of Land, Infrastructure, Transport and Travel of Japan, 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 as 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 2017, this number was reduced to 300-500 boats that could continue to arrive on various shores in 2015 and 2016.

In addition to large-scale biases, fluxes in Figure 2-10 may be different 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 North American Pacific 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.

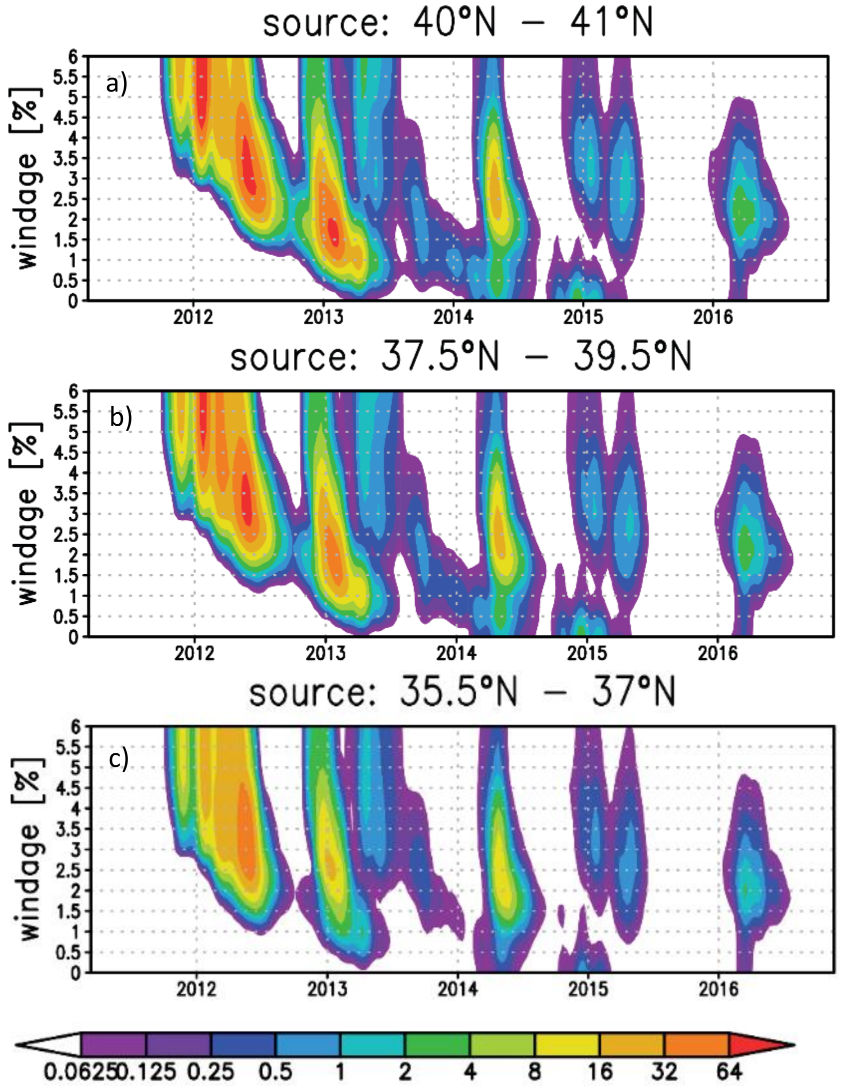

Figure 2-11. Sensitivity of fluxes to the latitude of source. Fluxes on the North American coastline in the SCUD simulations with sources of various windage debris located in the (a) northern, (b) central and (c) southern sector of the east coast of Honshu, affected by the Great Tsunami of 2011. Units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

Model comparison with observational reports from Hawaii

Another area where JTMD has been relatively well documented is the main Hawaiian Islands. Located in the central subtropical gyre, it receives lower-windage marine debris than typical for the North American Pacific coast. With a relatively short shoreline and relatively high density of population (say, compared to Alaska), many sites in 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 North American Pacific coast, where waves of debris have seasonal time scales and high probability to interact with a receiving beach, in Hawaii there is high probability for floating 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 have been 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 whether other shores did not receive boats or if the boats were not reported. The timeline of 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 some others do not.

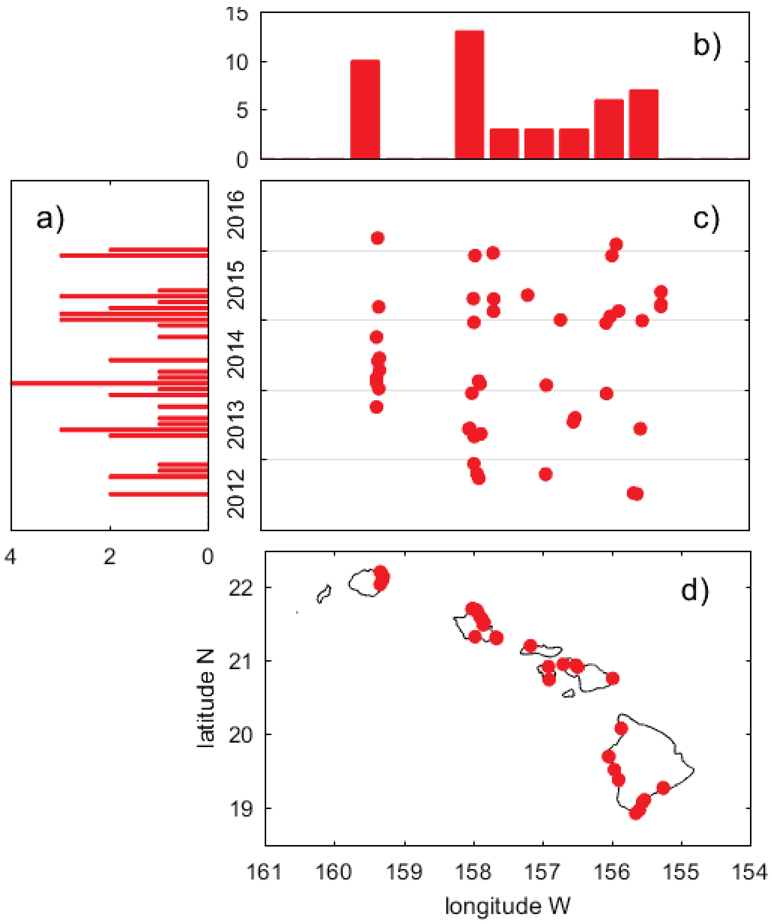

Figure 2-12. Reports of 45 JTMD boats from the main Hawaiian islands coastline. (a) Monthly number of reports. (b) Number of reports in 1/2-degree longitude bins. (c) Longitude-time diagram. (d) Location of reports relative to the shoreline.

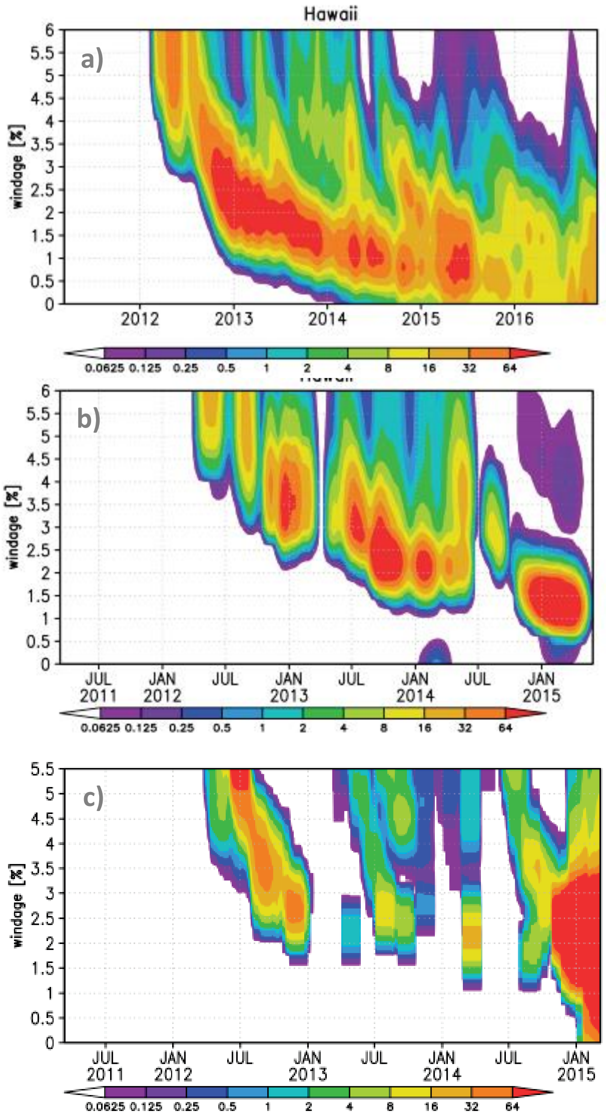

Figure 2-13. Model fluxes timelines on Hawaiian coast for different windages, calculated from (a) SCUD, (b) MOVE/K-7/SEA-GEARN, and (c) GNOME. Units are conventional and differ between the panels.

The complexity of the island dynamics is illustrated by the significant differences between the fluxes in the three project models (Figure 2-13). At the time of this report, no satisfactory correspondence has been 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 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.

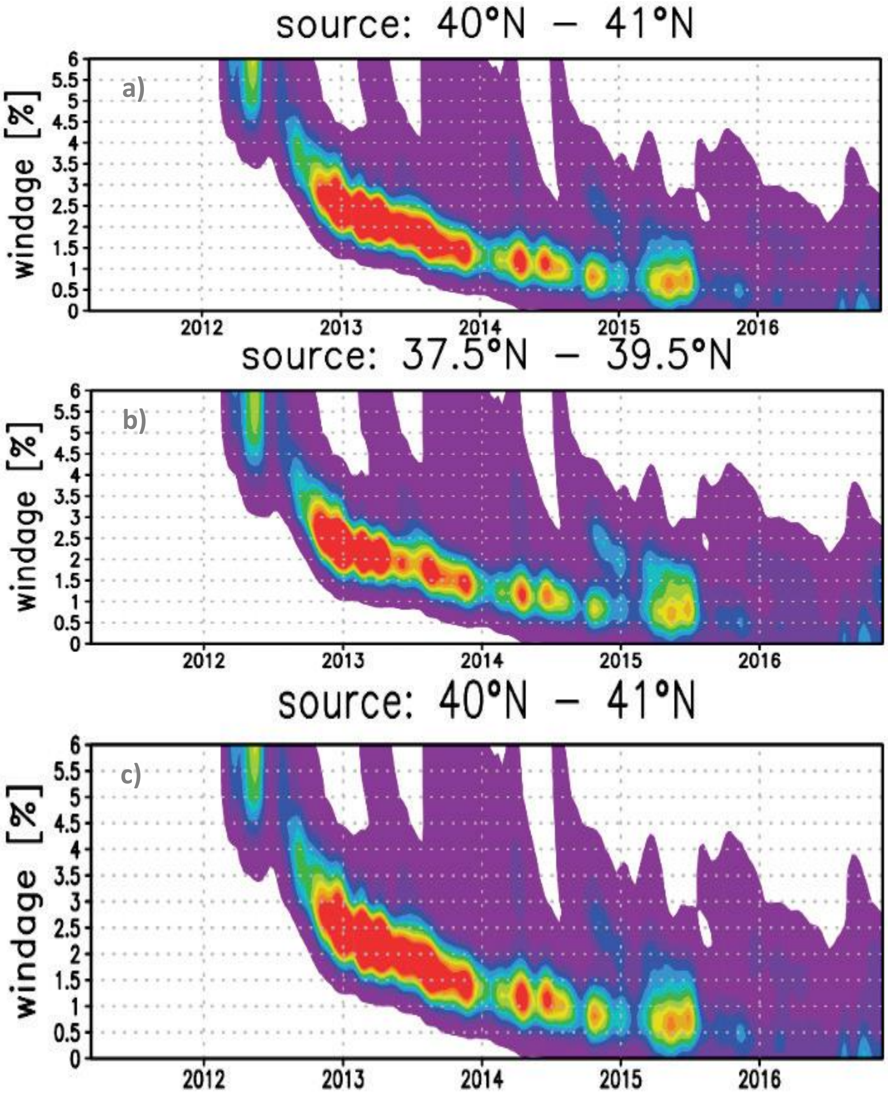

Figure 2-14. Sensitivity of debris fluxes to the latitude of source. Fluxes on the Hawaiian coastline in the SCUD simulations with sources of various windages located in the northern (a), central (b) and southern (c) sector of the east coast of Honshu, affected by the Great Tsunami of 2011. Units are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

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 distribution of boat reports in space (dots) 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 were not present. Such negative reports would be tremendously 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.

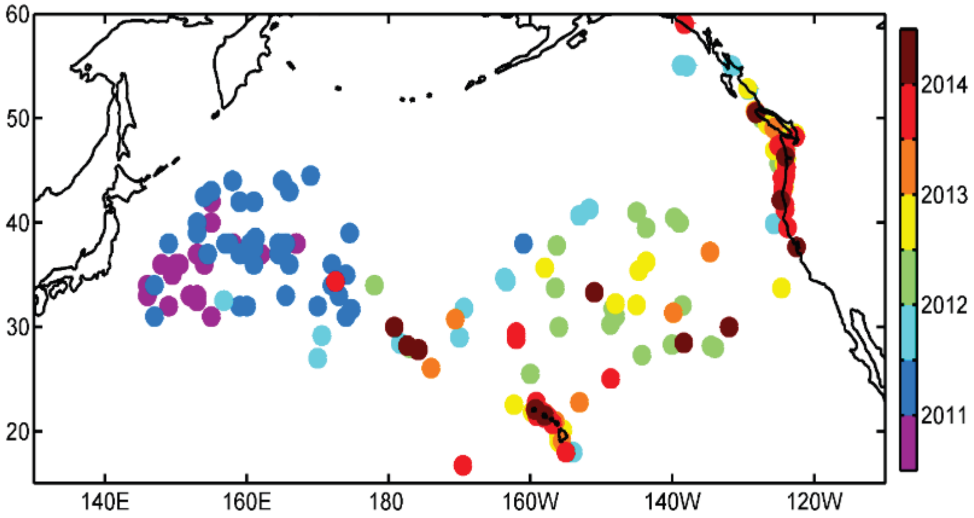

Figure 2-15. Reported locations of boats/skiffs/ships (dots or filled circles) and times (colors) of the reports. Color bar spans January 2011–December 2014 and labeled ticks mark central moments of the years.

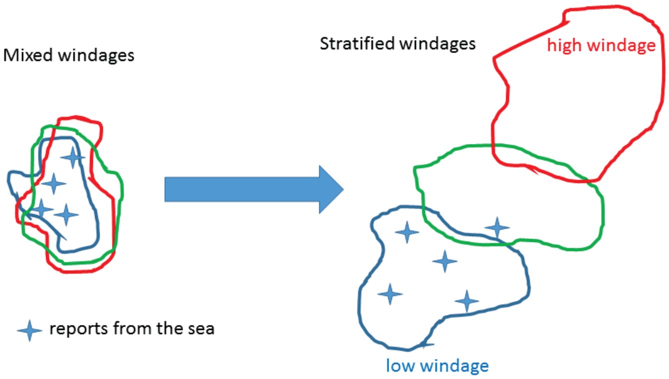

Figure 2-16. Illustration of the method of optimal windage estimate by subsampling model solution at locations/time of marine debris reports.

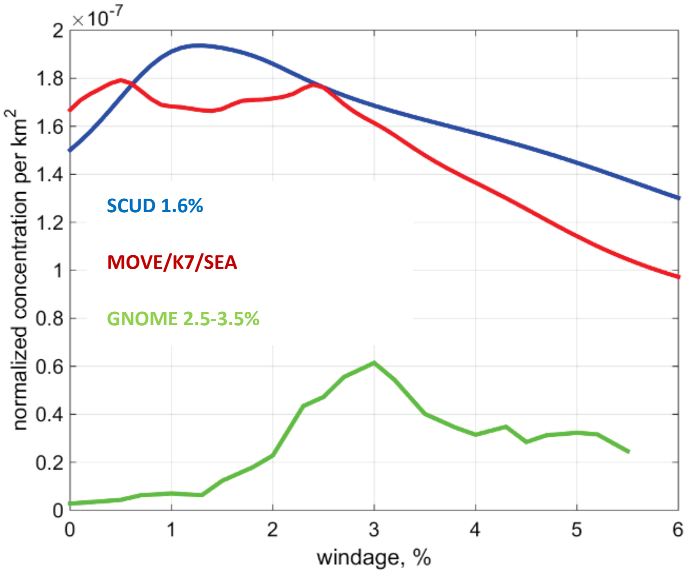

Figure 2-17. Mean tracer concentrations for SCUD (blue), MOVE/K7/SEA-GEARN (red) and GNOME (green) for different windage values averaged over locations and times of boat reports shown in Figure 2-15 and model solutions shown in Figures 2-5 to 2-7.

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 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 (for example, windage of the tracer).

The evolution of 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 an excellent agreement with similar estimates in Figure 2-10. At the same time, MOVE/K7/SEA-GEARN performed best at 0.5-2.5% windages that was somewhat lower than in Figure 2-10 – the reason for such discrepancy is currently not known.

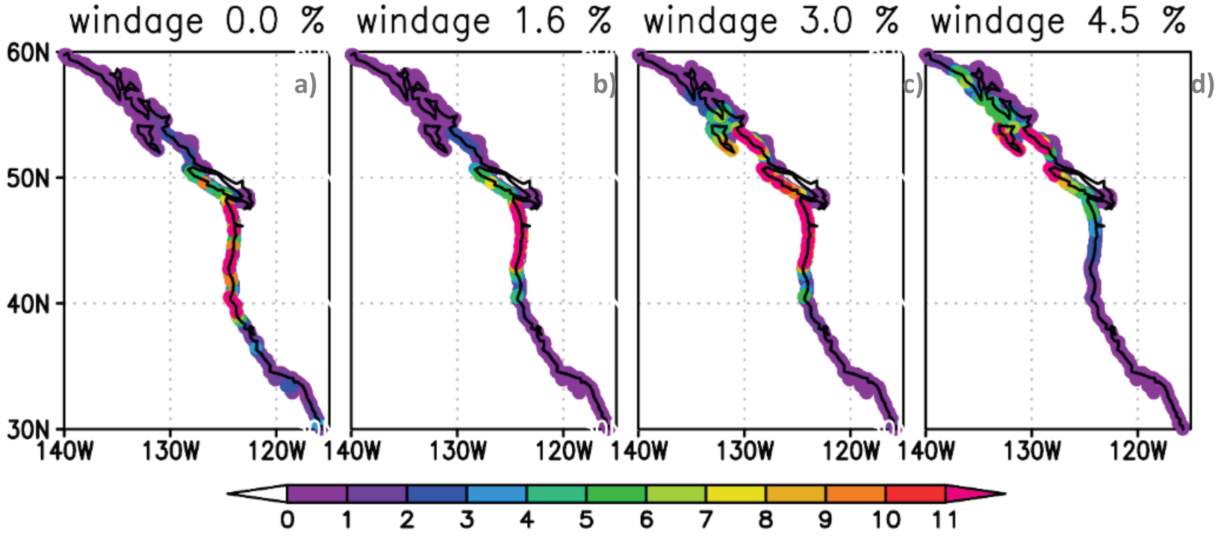

Figure 2-18. Relative amount of model tracer that washed onto the North American west coast in the SCUD runs between March 11, 2011 and March 10, 2016. Units are conventional. Windage values are (a) 0%, (b) 1.6%, (c) 3%, and (d) 4.5%. Units are conventional.

Patterns on shore

One of most challenging questions to 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 because observational data were not available on the model scale. Comparison between models and available JTMD reports was difficult because information on the coastline accessible to the JTMD 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 48N 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 46N, but this 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 this 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 from Portland.

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 a good agreement with boat reports as well as 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.

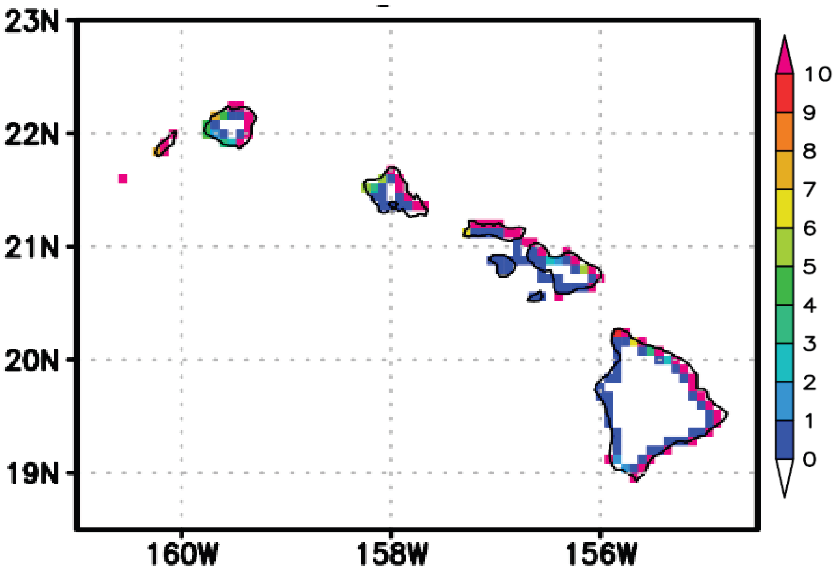

Figure 2-19. Relative amount of model tracer (with 3.0% windage) that washed on the Hawaiian coastline in the SCUD runs between March 11, 2011 and March 10, 2016. Units are conventional.

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. Error 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 very 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 in the US (point B), Figure 2-20b calculated using reverse equations shows its probable locations on January 1, 2012. The two PDFs can be combined and their product (logical operation “AND”) shown 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 the northern Honshu and were later reported from Oregon, Washington and Hawaii.

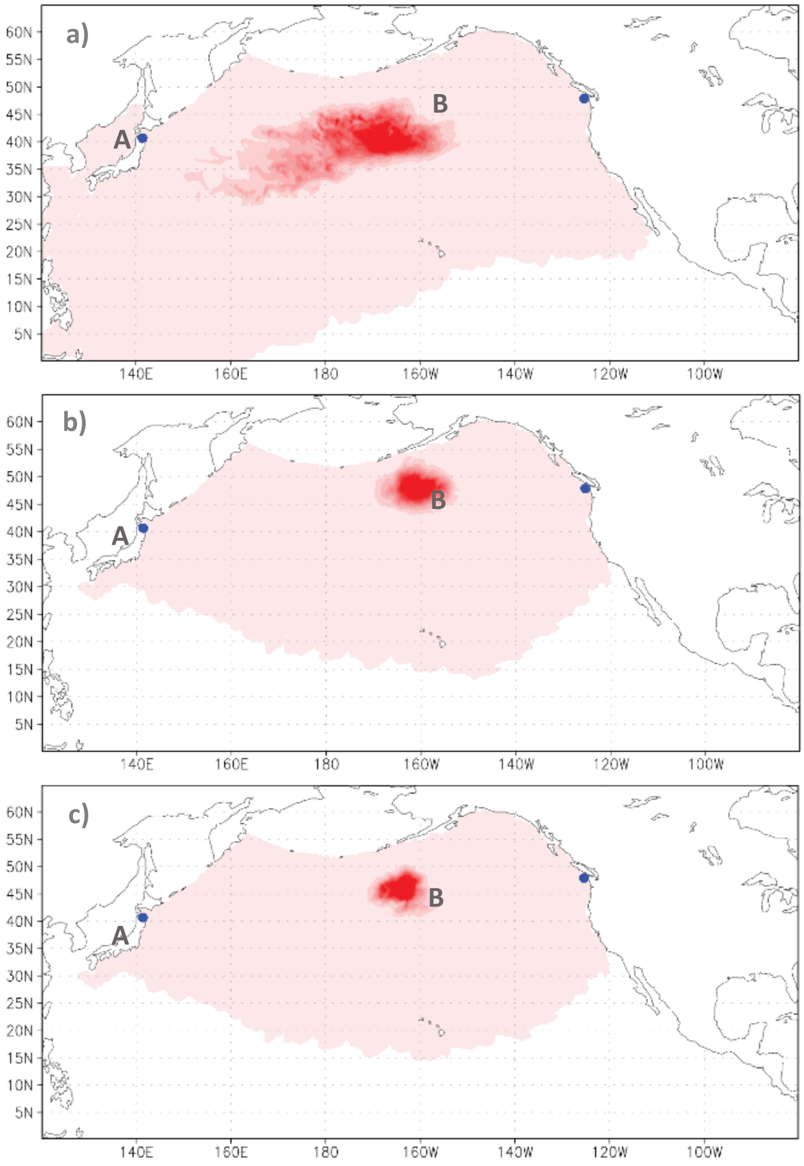

Figure 2-20. Probability density functions of model particle locations on January 1, 2012 for the particles that: (a) started from Japan on Mar 11, 2011 (point A), (b) ended in Washington state on Aug 15, 2012 (point B), and (c) combined probabilities of particles that both started at point A and ended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

Our new techniques allow the addition of practically any weak or strong constraints for various applications. For example, 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's 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 northeast Pacific (Figure 2-21d). In the course of the project, our technique demonstrated its power in many difficult applications. It 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 2-23a) and a similar boat (Figure 2-23b) that was found in Okinawa in 2016 (i.e. five years later).

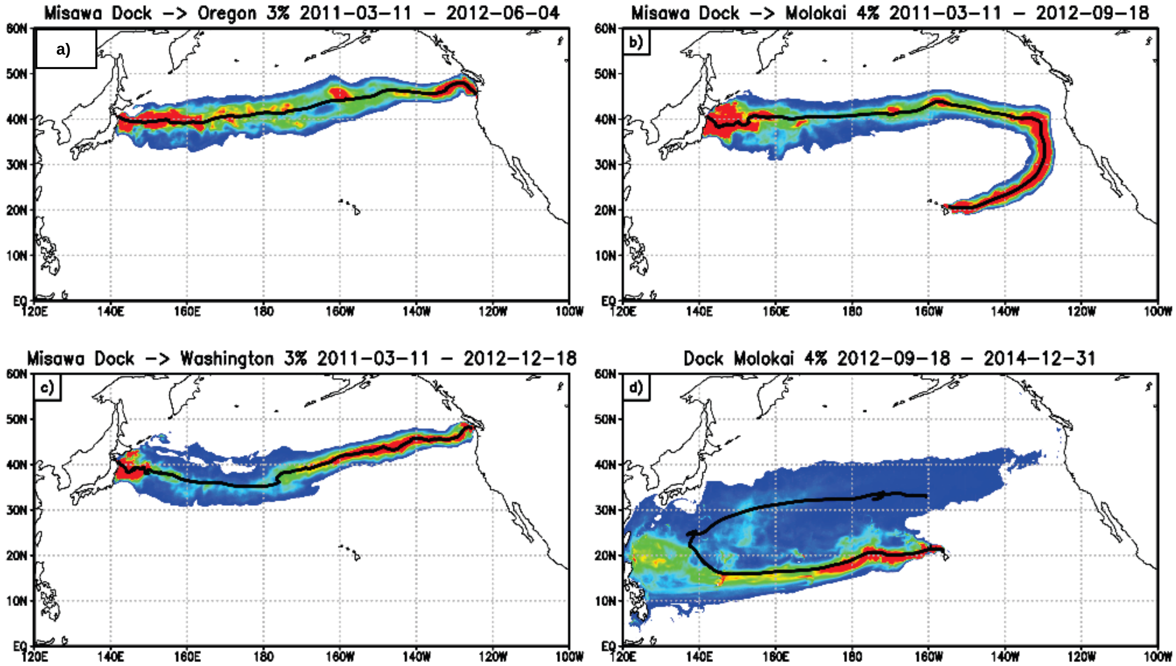

Figure 2-21. Probable visited locations (colors) and trajectories (lines) for Misawa docks, reported from (a) Oregon, (b) Washington, and (c) Hawaii. (d) Probable trajectory of the Molokai dock after drifting between Hawaiian Islands.

Similarly, other information can be derived from our methods. For example, Figure 2-22 shows probability distribution function (PDF) and probable timelines of the sea surface temperature (SST), estimated using AMSR 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 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. For example, in future studies, information about species found on JTMD items can be added to improve estimates of probable paths.

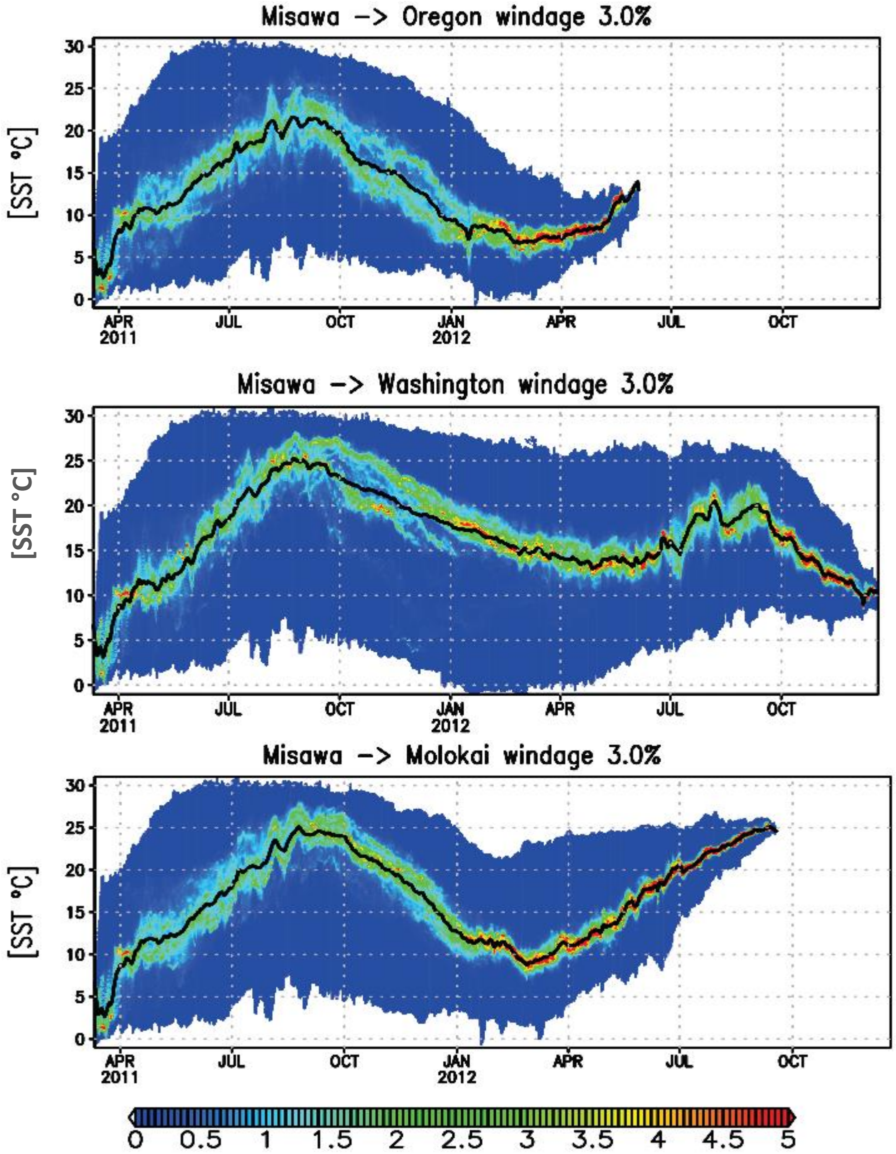

Figure 2-22. Probability density functions (colors) and probable timeline (lines) of satellite sea surface temperature (SST) experienced by Misawa docks along their probable paths.

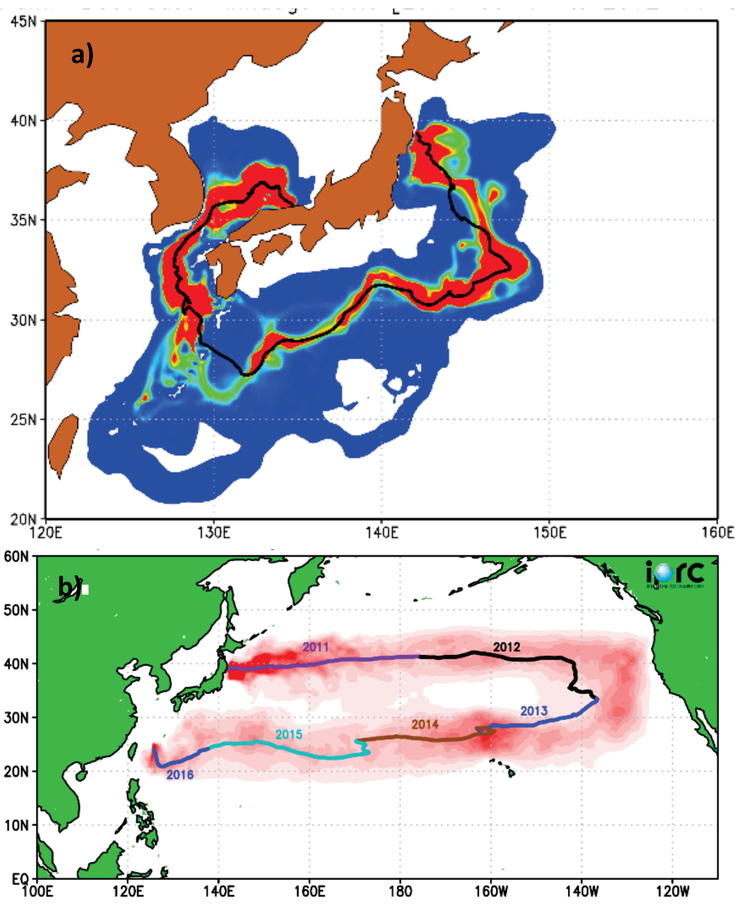

Figure 2-23. Probable visited locations (colors) and trajectories (lines) for the two JTMD boats found (a) December 31, 2011 near Kasumi on the west coast of Japan and (b) May 12, 2016 in Okinawa.

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 for the northern Honshu but also subtropical species, which suggested 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 continuous tracer source (at 0% windage) along the southern Honshu, Shikoku, and Kyushu. Despite a short lifetime span of the larvae (7-day e-folding decay), it was advected hundreds of kilometers eastward by the fast Kuroshio Extension (Figure 2-24a). JTMD tracer released north of the Kuroshio Extension also mainly drifted 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 160E (Figure 2-24c). Once attached to a JTMD item, larvae could develop into an adult species and continue the journey toward North America and Hawaii.

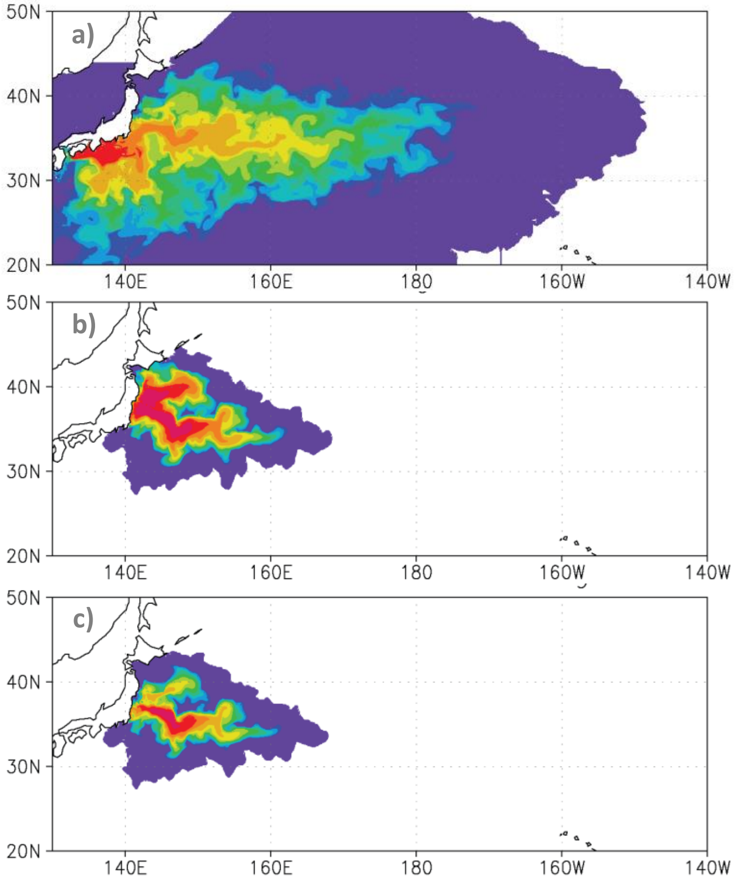

Figure 2-24. Interaction between tsunami debris and subtropical coastal species in SCUD simulations: (a) March 11, 2011 concentration of model larvae, continuously released from the south coast of Japan and having 7-day e-folding life span; (b) concentration of JTMD tracer with 2% windage; and (c) strength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

Temperature match between Japan and 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 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 Tsunami of 2011. Sea surface temperature (SST), 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 40N and corresponding to maximum JTMD generation (Figure 2-1) also had the broadest SST range, spanning 20 degrees Celsius; with a very strong seasonal cycle with temperatures below 5ºC in winter and above 25ºC in summer. The SST range east of Japan exceeded the one in North America by as much as double (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 30N. This suggestion was further confirmed by Figures 2-27a and b that show that nearshore SST conditions between Baja California and Alaska all fit in the temperature range of the east coast of Japan between 39 and 41N.

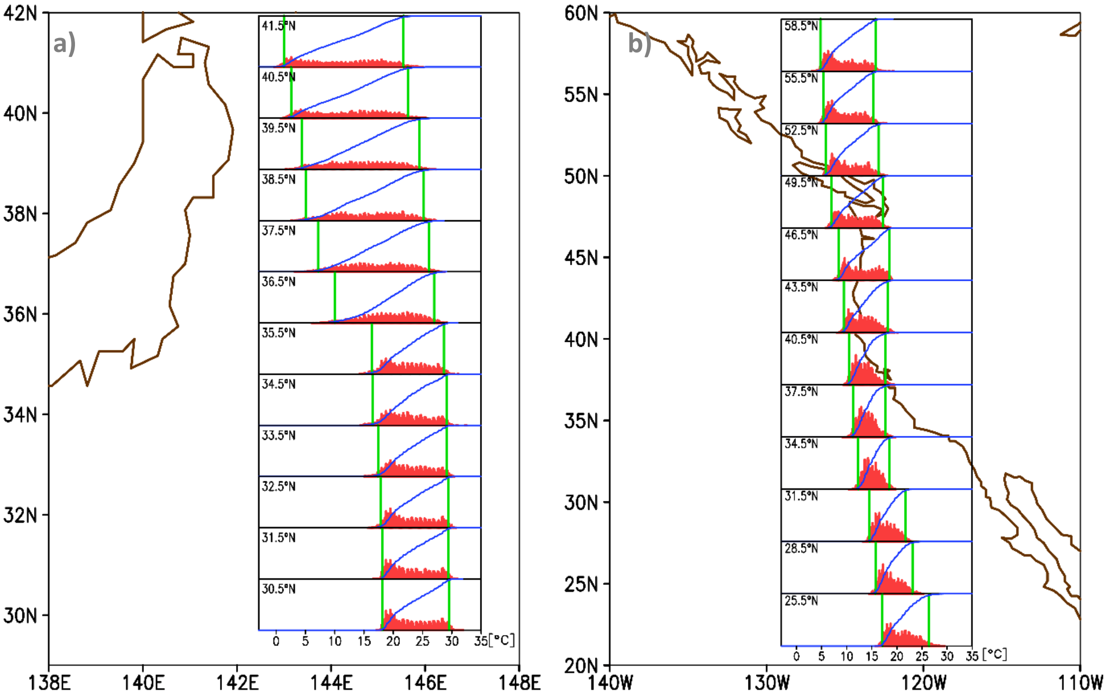

Figure 2-25. Probability density function (PDF) (red bars) of sea surface temperature at different locations along (a) the east coast of Japan and (b) the Pacific coast of North America, calculated from the AMSR satellite data. Blue lines are cumulative PDFs and green bars indicate sea surface temperature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

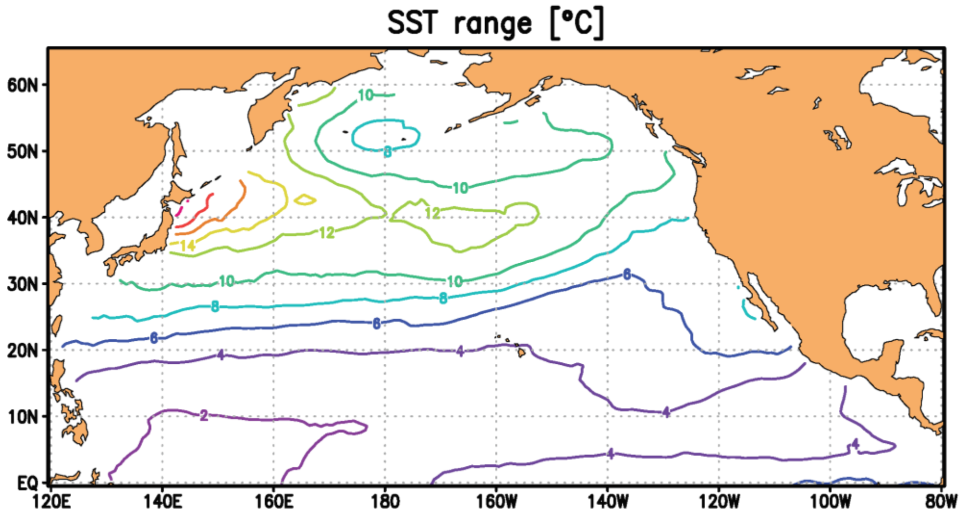

Figure 2-26. Sea surface temperature (SST) range in AMSR satellite data.

This pattern does not include Hawaii, where tropical temperatures are significantly higher, which suggests that species from the north of Japan will be less likely to survive. However, subtropical species that may have been picked 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 was an interesting and difficult task that requires future investigation and, importantly, sample collection from marine debris in the open ocean.

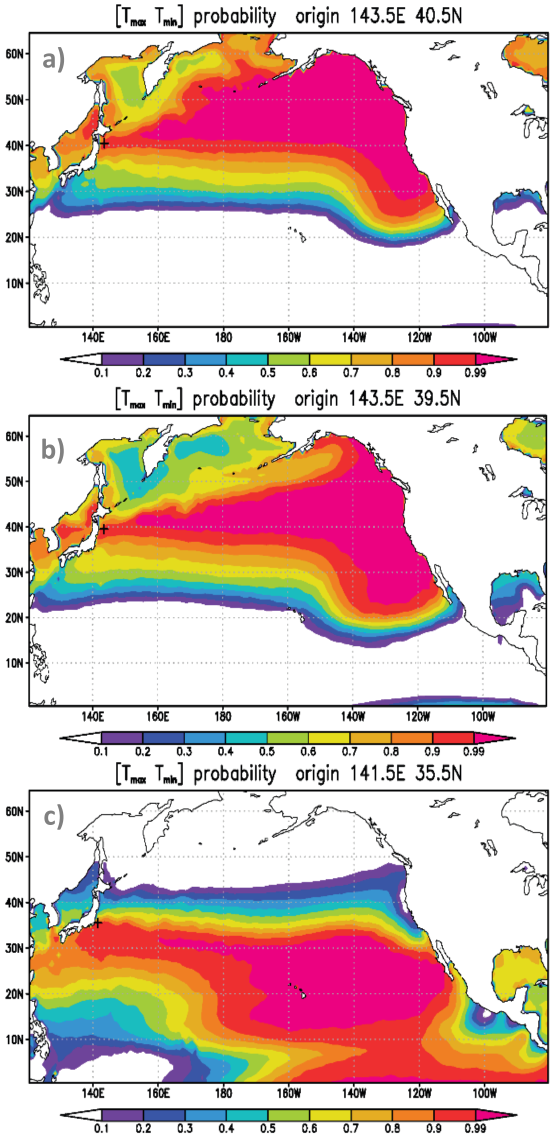

Figure 2-27. Degree of the sea surface temperature (SST) match with the climatology at select locations east of Japan (marked with crosses), calculated using AMSR satellite data. Model origin locations: a) 143.5E, 40.5N, b) 143.5E, 39.5N, and c) 141.5E, 35.5N.

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 verification and scaling using observational data and are available for the investigation of patterns and timelines 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.

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THEME II – Arrival of Debris

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

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Abstract

Marine debris is one of the leading threats to the ocean and the Great 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 timelines of tsunami marine debris. The increase in debris influx to surveyed Pacific North American and Hawaiian shorelines was substantial and significant, representing a 10 time 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 peaks in measured shoreline debris match the predictions made by the oceanographic models. The impacts of Japan tsunami marine debris (JTMD) are unknown and long term monitoring of coastal waters are required to detect alien species possibly introduced by the debris.

Introduction

The Great East Earthquake in Japan and resulting tsunami washed an estimated 5 million tons of debris into the Pacific Ocean (Ministry of the Environment, Japan 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

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[1] A version of this chapter is in preparation for publication in a peer-reviewed journal

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 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.

Photo credit: David Baxter

Monitoring and removal of shoreline debris has been ongoing since the 1990s (Ribic et al. 2012; Morishige et al. 2007). 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 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 clean ups 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 Tsunami of 2011 and 3) compare to oceanographic modeling predictions. In short, we ask whether we can we detect the signal of the tsunami debris against the background of ongoing marine debris.

Materials and Methods

Shoreline monitoring


Photo credit: Linda Leach (CBC)

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 100m stretch of beach every 28 days. All debris items are recorded and removed from the shoreline. Surveys were conducted by citizen science groups or government staff, and depending on weather and tides, the amount of beach and monthly schedule sometimes varied (Opfer et al. 2012). For each survey, the incidence of large items (greater than 30 cm) was specifically recorded and additional information and photos of the items were provided by surveyors. Between March 2012 and December 2015, over 1100 surveys have been 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 Olympic Coast National Marine Sanctuary (OCNMS) 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 State from 2001-2011. All debris was removed from a 500m stretch of beach at each site and the number of debris items in each of the 30 indicator categories was recorded (Supplementary Materials). Indicator items were chosen to represent different sources of debris (land, ocean, and general source debris); the pre-2011 National Marine Debris Monitoring Program (NMDMP) 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). 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). The mean number of debris items recorded per 100 m stretch of beach per day was analyzed and ANOVA with Tukey's b post-hoc statistical tests were used to test for differences between years and states or provinces.

After the Great 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) model were used to study particle and tracer motions within a range of windage parameters, describing the direct effect of the wind on items floating on the ocean surface. SCUD is an empirical, diagnostic model that is forced with data from satellite altimetry and scatterometry and calibrated on a ½-degree global grid using trajectories of satellite-tracked drifting buoys (Maximenko and Hafner 2010). The model calculated tracer evolution released on March 11, 2011 in the model domains along the east coast of Honshu for 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 100m of shoreline per day between 2003-2012 to mean 0.29 debris items per 100m per day from 2013-2015. This was an almost ten-fold increase in debris influx to sites in northern Washington State over that recorded in the nine 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 100m 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).

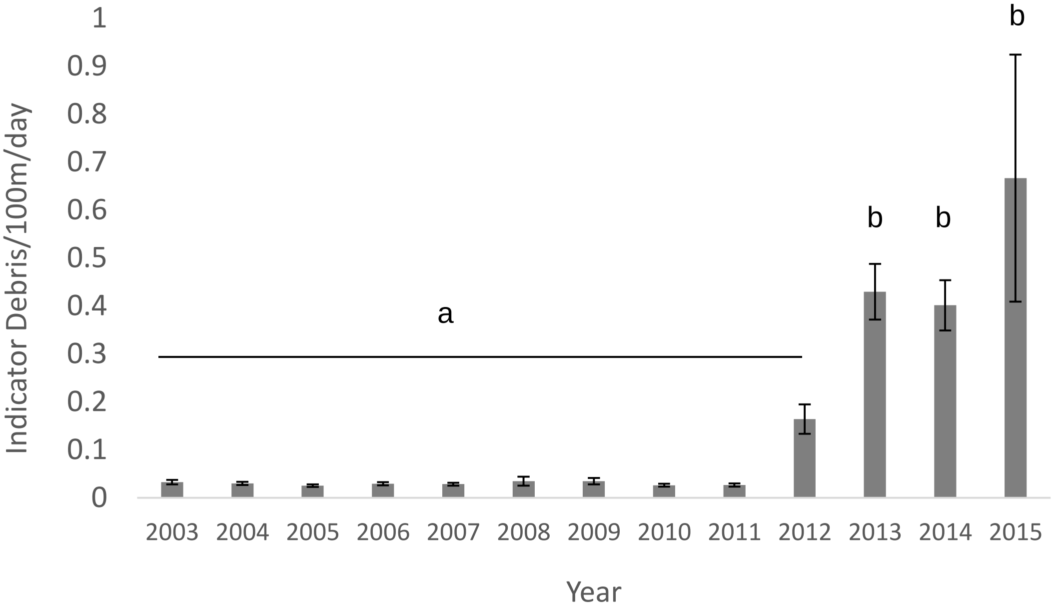

Figure 3-1. Mean yearly debris influx of indicator items from 2003-2015 at sites in northern Washington State. Letters denote significantly different groups using Tukeys HSD posthoc comparisons).

Across the West Coast of the US, there were peaks in all debris items (not just indicator items) in May 2012, 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 100m per day. Mean monthly debris influx for all debris items (2012-2015) ranged from 0.5 to 13.8 debris items per 100 m per day, with a global mean of 2.7.

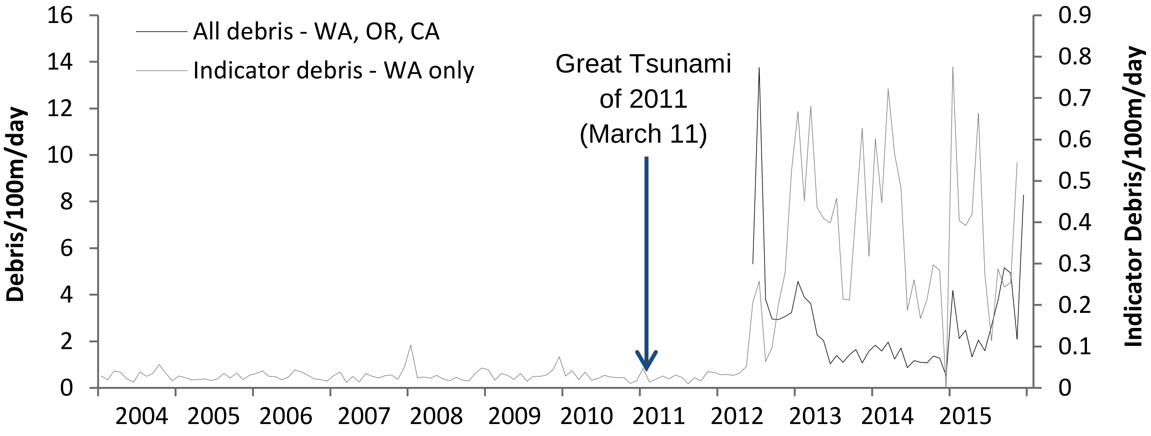

Figure 3-2. Mean monthly debris influx of indicator items (indicator debris items/100 m/day) from 2004-2015 at sites in northern Washington State (grey line) and mean monthly influx of all debris items (debris items/100 m/day) for Washington State, Oregon and California from 2012-2015 (black line).

Across all the states and provinces of study, Hawaii, USA received the highest mean debris items over the post-tsunami study period (2012-2015) (Figure 3-3). British Columbia, Canada has the second highest mean debris influx in this time period, driven by a few surveys in the islands of Haida Gwaii (northern BC) with high numbers of large Styrofoam pieces. Alaska had few accumulation surveys to analyze and has not been included in the figures. The total amounts of debris arriving monthly to actively monitored North American coastlines in the post-tsunami months ranged from 150-1951 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).

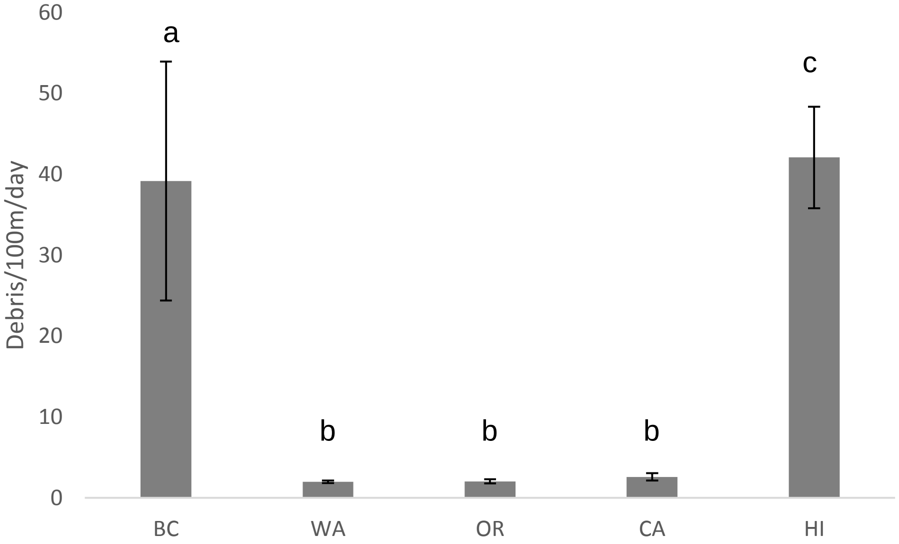

Figure 3-3. Mean debris item arrival (debris/100m/day) from 2012-2015 by province/state. BC = British Columbia, WA = Washington State, OR = Oregon, CA = California, and HI = Hawaii. Letters denote statistically different subgroups.

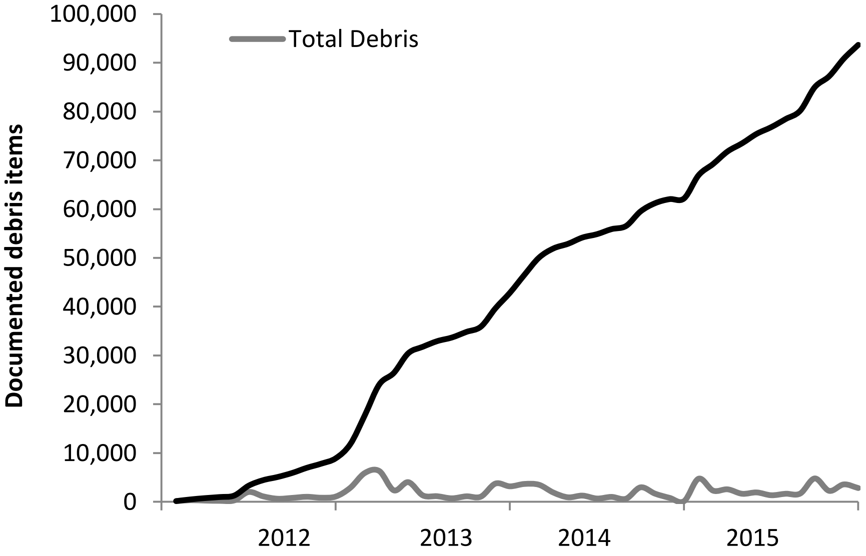

Figure 3-4. Total (grey) and cumulative (black) number of documented debris items arriving to monitored shoreline sites (excluding Hawaii) over time (2012-2015).

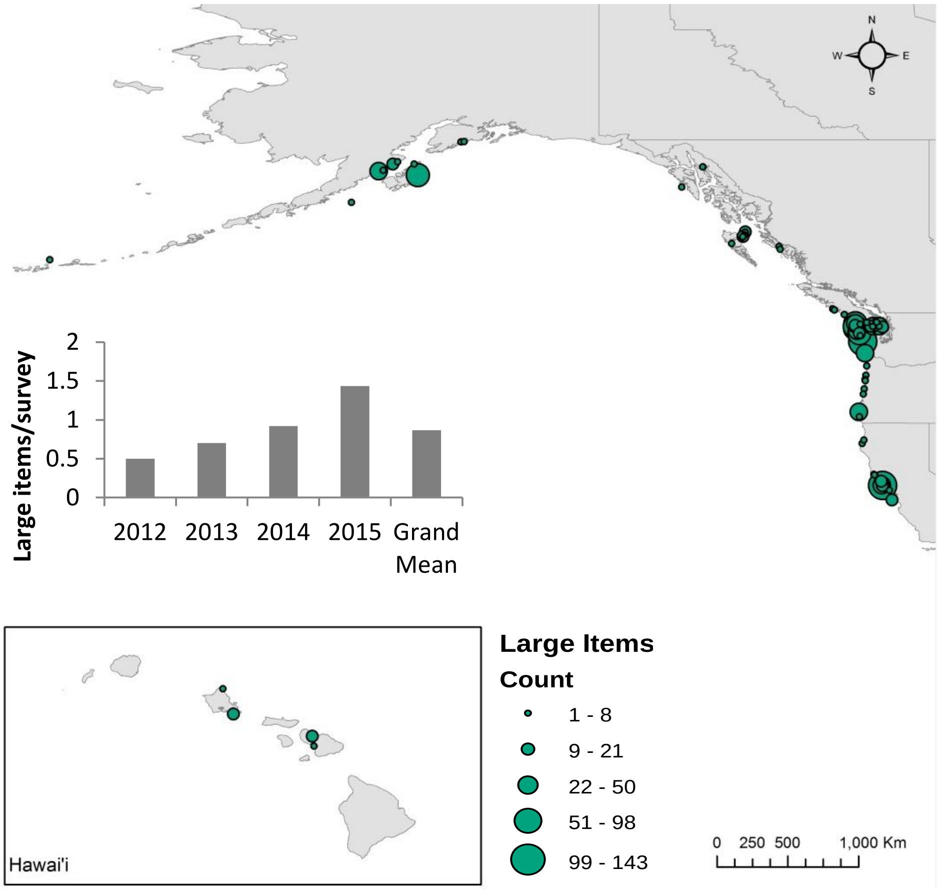

Figure 3-5. Map of large item reports per survey, circles of increasing size represent increasing numbers of large items recorded. Inset shows large items per survey between 2012 and 2015 in Hawaii.

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/shoreline, 736 items total), followed by California (7.7 items/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 neighboring 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 Tsunami of 2011 in each of the temporal peaks (Figure 3-6). The sightings were significantly spatially clustered at a mean distance of 16.268km (nearest neighbour Euclidean distance: observed mean distance = 16.3km, expected mean distance = 137.205 km, nearest neighbour ration = 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 Tsunami of 2011 (33/202 reported). Many of these vessels had registration numbers or vessel names that could be more easily traced and officially confirmed as tsunami debris.

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 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**

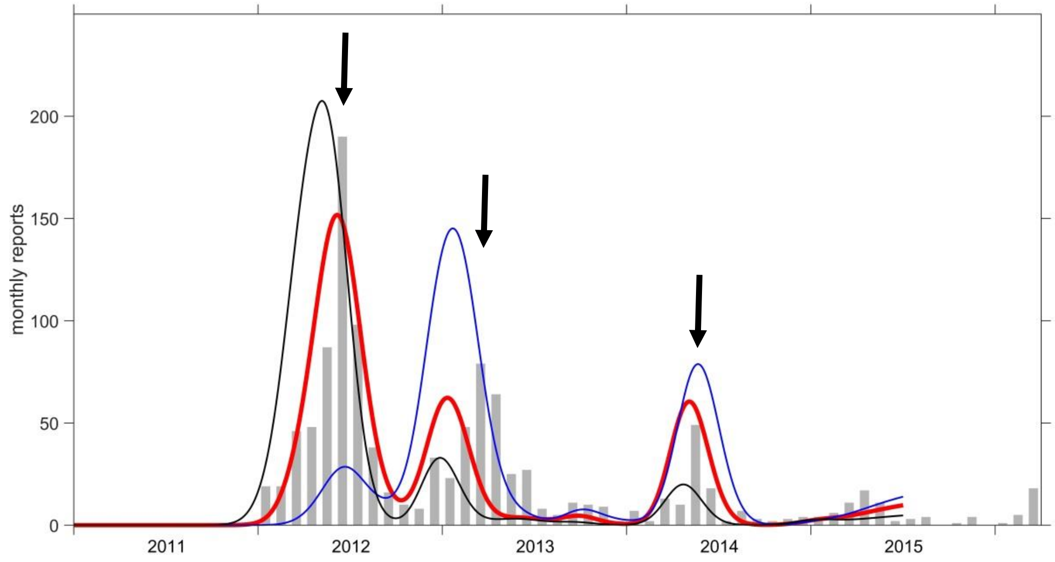

Figure 3-6. Temporal peaks in disaster debris reports for North American landfall (grey bars), as of April 13, 2016, and predicted monthly debris arrival from SCUD model. Lines represent model solutions for differing windage values: 1.5% (blue), 2.2% (red), and 3.0% (black), arrows indicate temporal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

Modeling predictions

The model solutions corresponded with observations by capturing all three main temporal peaks in the disaster debris reports and the shoreline debris arrival data, although disagree somewhat in the magnitude of the peaks (Figure 3-6). Model solution indicates temporal peaks in June 2012, Jan 2013, and May 2014 (arrows in Figure 3-6). Interestingly, for 2013 the model solutions lead the observations by two 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 $\rho = 0.517$, $p = 0.001$, $R^2 = 0.441$).

Changes in composition of JTMD landings over time can lead to changes in the optimal windage, causing the mismatch between sightings and model solution (Figure 3-6). High-windage tracer arrives earlier than low windage 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.

Discussion

Unprecedented influx of marine debris

The Great Tsunami of 2011 caused a significant and substantial influx of debris to North American shorelines 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 exists, an increase of more than 10 times (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 in North America and 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 North Pacific coast. Ribic et al (2012) reported a mean of 0.2 marine debris indicator items per 100m per day for the North Pacific Coast from 1998-2007. 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 North Pacific 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 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, microplastic 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.


Photo credit: N. Maximenko

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 BC 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. Temporal trends in Hawaii were more variable and the peaks from the Great 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 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 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 (Maximenko pers. obs.).


Photo credit: Lightspeed Digital

While previous surveys documented declining or stable debris influx across the Pacific coast of North America and Hawaii (Ribic et al. 2012), the Great 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.

Potential ecological impact of debris

A substantial increase in marine debris influx increases the risk of impacts similar to marine debris in general – entanglement and ingestion, provision of new habitat, dispersal via rafting, and assemblage-level effects (Gall and Thompson 2015). In contrast to general marine debris, debris resulting from the Great Tsunami of 2011 had a specific start position and time and differing debris types. The tsunami debris field contained similar household debris but also coastal floating infrastructure such as aquaculture equipment, docks and wharves, large and small vessels, as well as construction materials and vegetation (NOAA Marine Debris Program

2015). Plastic debris has a suite of impacts such as entanglement, ingestion, addition of habitat, smothering, and chemical contamination (Gall and Thompson 2015; Rochman et al. 2016).

The directional drift from Japan to North America combined with an unknown residency in coastal Japanese waters has increased the biodiversity and fitness of attached sessile fouling organisms and hitchhiking organisms (see Chapters 7 and 11). Those species native to the western Pacific are at risk of arriving, establishing, and spreading in the eastern Pacific, potentially becoming invasive species (see Chapter 15). Debris items that were in the coastal waters may have had established fouling communities that were taken with the debris item during the tsunami. Terrestrial origin debris items (logs, lumber, household items and small vessels) may have spent weeks in the coastal Japanese waters where marine species may have settled and became attached. Hundreds of Japanese species from a diverse set of taxa arrived in North America and Hawaii, associated with tsunami debris (Calder et al. 2014; Chapter 7 and 9). Mussels arrived alive and in reproductive condition (see Chapter 11). The risk of these species to the eastern Pacific is under investigation and surveys are underway to monitor for new introductions (see Chapters 13-14).

The arrival of high numbers of large marine debris items brings another set of potential impacts. Large items may carry higher numbers of individuals and higher diversity of species which could pose a greater risk of species introductions. Large items could also have physical impacts on the receiving coastal ecosystem, scouring soft substrate and sessile organisms, shading marine plants and algae, and dislodgement, dismemberment, and mortality of coastal organisms are possible, but have not been documented specifically from this event. Long-term monitoring is required in order to fully investigate the physical and ecological impacts of this event.

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


Photo credit: Lightspeed Digital

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

Conclusion

There was a significant increase in debris from baseline levels in west coast of North America and Hawaii in the years following the Great 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 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 the MDMAP program provided crucial data in the wake of this unprecedented event and monitoring for potential impacts, including those from potential invasive species, should be continued in the future.

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Appendices

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

Eleven sites were consecutively surveyed with the pre-2012 and post-2012 survey methodology in northern Washington State: Abbey Island, Elwha West, Hobuck, Hoko River, Norwegian Memorial, Roosevelt, Ruby Beach, Thompson Spit, Tongue Point, Tsoo-yess South, Wa-atch (Supplementary Figure 3-1).

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

The indicator categories used by the NMDMP (pre-2011) were compared to those used in the 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-2012 (NMDMP) monitoring protocol and the post-2012 (MDMAP) protocol. "=" signifies equivalent categories, "no" indicates no equivalent, "combine" indicated finer resolution in either protocol so the categories were summed together.

Pre-2012 category	Comparison	Post-2012 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 & 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 ≥ 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 ≥ 1 m	No	Plastic//
Plastic bags with seam < 1 m	combine	Plastic/Bags
Plastic bags with seam ≥ 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 pl. bottles		Plastic//Other jugs/Containers
Rope ≥ 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	

THEME II – Arrival of Debris

Chapter 4: Webcam monitoring of marine and tsunami debris arrival in North America[2]

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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) were 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 onshore-ward 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 (onshore-ward) winds prevailed in winter at the spring tides. It is therefore reasonable to consider that the wind setup resulted in the re-drifting of debris during the westerly (onshore-ward) winds at spring tides (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 were as follows: about 3% of JTMD was accumulated on the US 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.

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[2] A version of this chapter is in review for publication in a peer-reviewed journal

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 out 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 North American and Pacific Islands' coasts, which continue even at the present time. In particular, attention was focused on coastal Japanese species carried by JTMD because these invasive species might damage the indigenous marine ecosystems (see Chapters 7-12)

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 western United States and Canadian coasts over a period longer than one year (including seasonality), and with a monitoring interval shorter than a week. Consequently, there is no way of knowing critical factors governing the temporal variations of debris abundance on these beaches. In the present study, we installed a webcam system (originally described by Kako et al. 2010; Kataoka et al. 2012) on a beach along the western United States coast to hourly monitor the marine debris abundance over a one-year period. Using this one-year record, we then establish a numerical model to estimate the abundance of the JTMD washed ashore on the western US and Canadian coasts.

Methods

We installed a webcam overlooking a beach in Newport, Oregon, directly facing the North Pacific (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) were littered. In this study, beach photographs were taken every 60 minutes during daytime (10 times from AM 9:00 to PM 6:00 in the Pacific Standard Time of the United States), beginning 3 April, 2015. Analysis was conducted on photographs captured through 31 March, 2016. The area within the entire panorama measures approximately of 60-m and 70-m length 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 have been opened publicly on our website (http://nilim-camera1.eco.coocan.jp/webcam/index.html). In the present 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 to the debris littered on the beach. In particular, we should note that the actual JTMD is difficult to distinguish on the beach, unless the debris source can be suggested by Japanese characters printed on the debris surface, and the characters are sufficiently large to be identified on the photographs.

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 the monitoring. Hereinafter, 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, while those taken during foggy and/or rainy period were removed. Thereafter, the observer identified the marine debris regardless of their sizes, as shown in red circles in Figure 4-2b. If the 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, the visual observations were conducted twice by different observers to double-check the omissions and/or duplications of the marine debris.

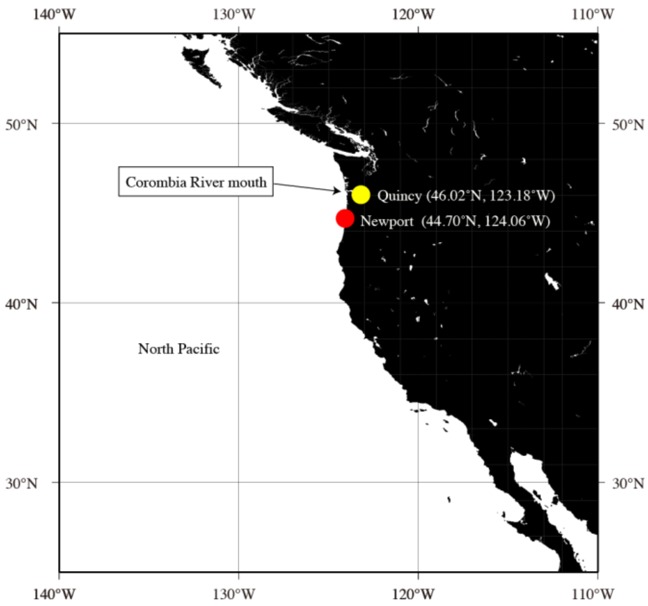


Figure 4-1. Map showing the locations of the webcam monitoring site (in Newport) and the Quincy observatory (measures of river discharge) in relation to the Columbia River mouth (Left) and photo of webcam system in place (Right).

In the present study, 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 was 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 therefore 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, they 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 one when southerly winds occurred ($N = N+1$ at $V > 0$; coastal downwelling), while the debris abundance on the beach decreases when the onshore-ward wind speed became higher than its temporal average at spring tides ($N \rightarrow 0$ at $U >$ average over the entire period; wind setup). The variation in marine debris abundance over time at the single webcam system location were then extrapolated to a larger area using the results from the British Columbia aerial surveys and image analysis (see Chapter 5).

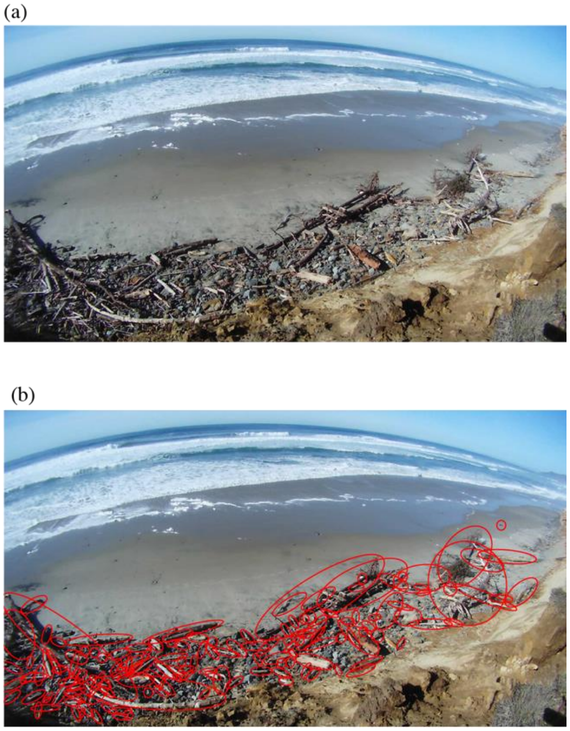


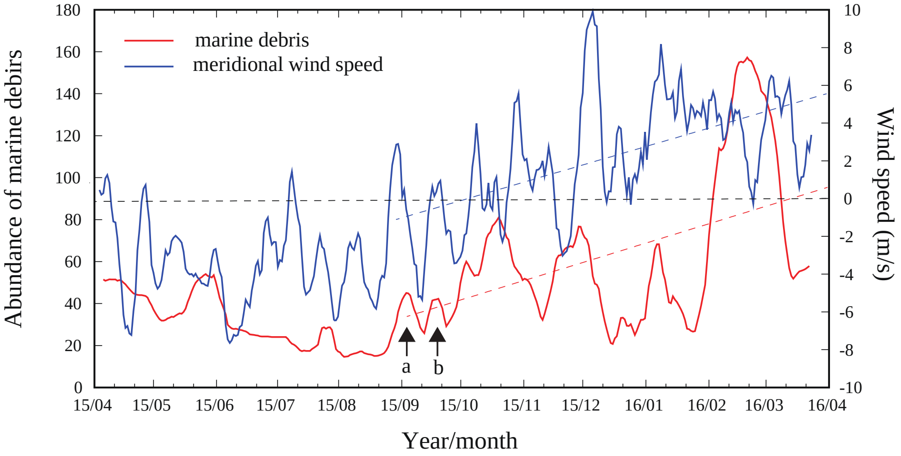
Figure 4-1. Webcam photographs of Newport Beach on February 25, 2016; a) Original photograph and b) marine debris (surrounded by red circles) identified on the photograph by visual observation.

Results and Discussion

The meridional wind component was responsible for the seasonal (summer to winter) increase of the 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 to 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 the coastal upwelling/downwelling and their associated cross-shore Ekman flows. In fact, it has been well known that the coastal upwelling occurs along the western US coasts, 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 onshore-ward Ekman transport carried marine debris toward the coast, and that the debris littered on the beach increased thereafter. Meanwhile, the beach litter decreased when drifting marine debris was prevented from approaching the coast because of the offshore-ward 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 the marine debris decreased when the westerly (onshore-ward) winds prevailed in winter. One may consider that the debris abundance varied in a non-intuitive manner, because onshore-ward 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 appeared when westerly winds prevailed at spring tides (gray bars in Figure 4-3b).

(a) vs. meridional wind speed



(b) vs. zonal wind speed

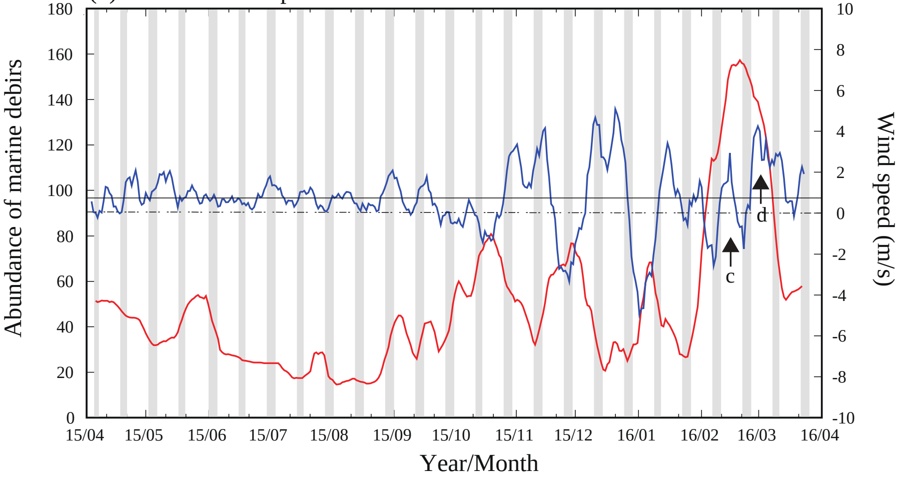


Figure 4-3. Comparison of the marine debris abundance with wind speed components (7-day running mean). The debris abundance (blue) is depicted in relation to a) the meridional wind speed, and b) zonal wind speed. Grey bars in panel b indicate the period of the spring tides.

It is therefore reasonable to consider that the wind setup resulted in the re-drifting of debris during the westerly (onshore-ward) winds at spring tides (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 (middle of Figure 4-4). Thus, it is likely that the seawater occupied over the entire beach mostly "swept" the marine debris (December 13; lower in Figure 4-**4**), which had been accumulated on the beach until the occurrence of the wind setup (upper in Figure 4-4).

Figure 4-4. Photographs of the day before (top, December 9, 2015), during which (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 the storm on December 11.

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 were 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 western US and Canadian coasts because the above model 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.

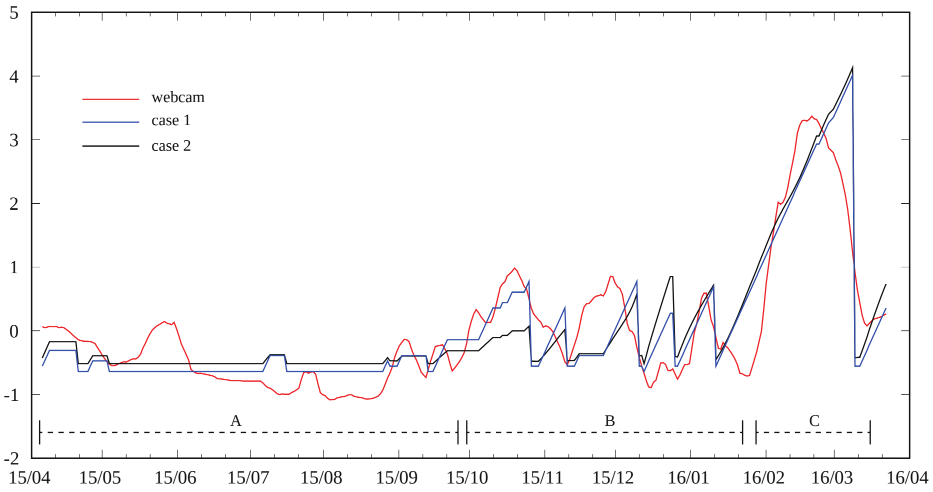


Figure 4-5. Time series of abundance of the webcam-observed (red curve) and modeled (blue curve) marine debris. (Case 2 (black curve) was not used in this report).

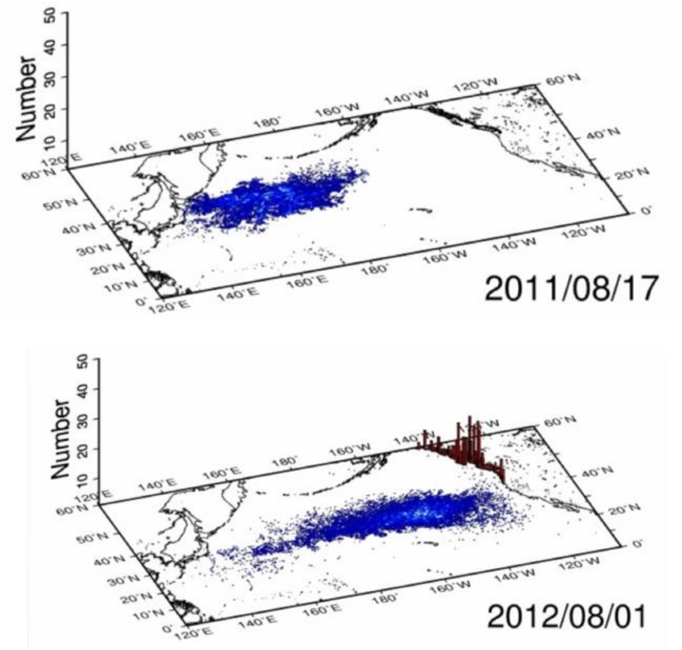


Figure 4-6. Two snapshots of the Particle Tracking Model (PTM) combined with the sub-model.

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 the criterion in the sub-model. The PTM uses surface ocean currents provided by the HYCOM (https://hycom.org), and ASCAT winds are used for both the PTM and sub-model. 50,000 model particles were released off the Sanriku coast, Japan, on March 11, 2011, and thereafter five-year computation was conducted. An advantage of the combination of the sub-model 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 the aerial photography (see Chapter 5), and validated the capability of the combination of PTM and sub-model to compute the abundance of JTMD washed ashore actually on the beach (Figure 4-7).

In summary, the abundance integrated over the five years (Figure 4-8) demonstrated that the JTMD has not washed ashore homogeneously on the entire West Coast of the US and Canadian beaches. Indeed, the JTMD have 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 Central Coast of British Columbia, which might act as a “gateway” of invasive species carried by the JTMD.

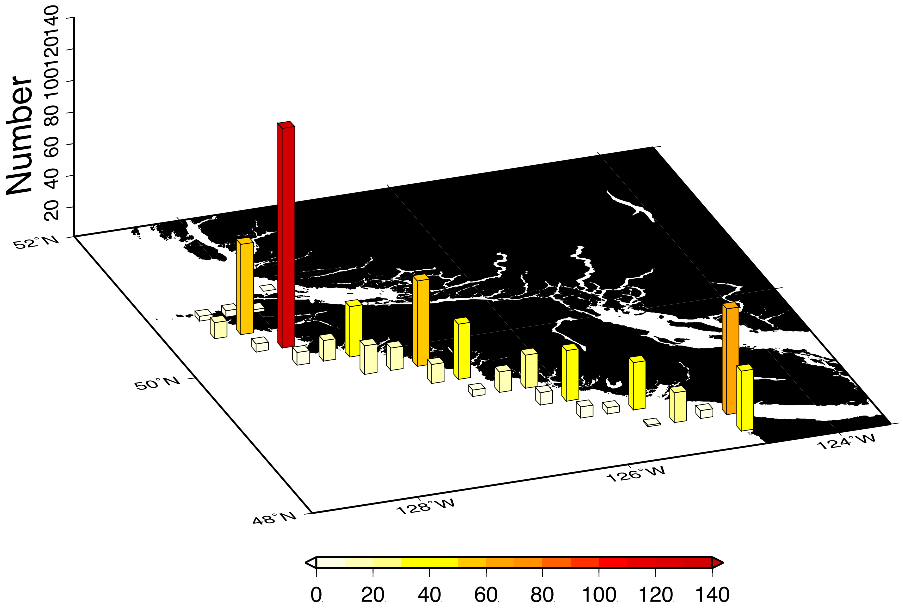


Figure 4-7. Modeled particle abundance averaged on the same day of the aerial photography survey in Figure 4-3.

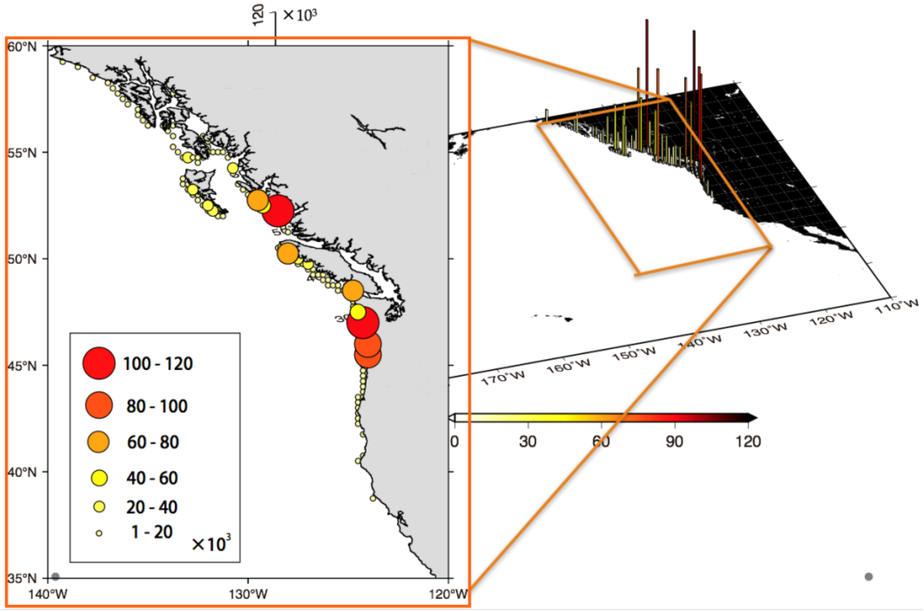


Figure 4-8. Particle abundance integrated over 5-year computational period. Particle numbers washed ashore on the beach grid cells are represented by the bar height, and are also represented by circle diameters in the enlarged map in the left panel.

Conclusions

This was the first installation of a webcam monitoring system in the US 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 US and Canadian coasts along, we estimated where and how much marine debris, and therefore JTMD , could have washed ashore. Based on the webcam monitoring, aerial photography, and Particle Tracking Model experiments, our estimates were as follows: about 3% of JTMD could have accumulated on the US and Canadian beaches, and that large amounts of JTMD were likely to have washed ashore on the relatively narrow areas around Oregon and Washington State, Central Coast and Vancouver Island, British Columbia.

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THEME II – Arrival of Debris

Chapter 5: Surveillance of debris in British Columbia, Canada[3]

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Abstract

An image analysis technique was established to quantify the abundance of marine macro-debris (debris abundance) with high spatial resolution using archived aerial photographs. The photographs were processed by projective transformation, and by extraction of pixels of marine debris based on their colors. 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 covers in Vancouver Island, Canada 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). The accumulation occurred especially in fall and winter when these oceanic and atmospheric conditions became favorable for marine debris to wash ashore. Therefore, the 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 (Gall and Thompson, 2015; Laist 1997), and the impact of microplastics, which is plastics smaller than 5 mm diameter, on marine ecosystems has become an emerging concern (Andrady 2011; Wright et al. 2013). In addition, marine debris provide new habitat and facilitate

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[3] A version of this chapter has been submitted to a peer-reviewed journal.


Photo credit: Lightspeed Digital

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 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 adverse impacts on the marine environment and/or ecosystems (Barnes et al. 2009). Debris abundance is most visible and noticeable on shorelines where they wash 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). Marine debris, originating from both land and sea-based sources of the world, could increase monotonously each year, corresponding to the global plastic production (Jambeck et al. 2015). In addition, marine debris can be re-suspended from the beach as nearshore hydrodynamics wash it 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, quantifying and reducing the debris abundance by beach monitoring and cleanup activities are both important activities to prevent marine debris from re-entering the ocean at the secondary sources. Furthermore, identifying areas and patterns of debris abundance can assist in the prioritization and allocation of monitoring and cleanup activities to remove debris from marine environments.

A number of methods have been developed to quantify the debris abundance on shorelines (e.g., Ge et al. 2016; Kako et al. 2010; Kataoka et al. 2012; Veenstra and Churnside 2012). Beach surveys, often conducted using 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 the aerial surveys can widely cover remote areas quickly and relatively easily, their measurement accuracy


Photo credit: Lightspeed Digital

should be evaluated through ground-truth survey techniques. Meanwhile, an alternative method for remotely monitoring 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 the webcam monitoring also requires the ground-truth data to validate the observed area. The application of image analysis techniques to the above aerial photographs may allow us to quantify the debris abundance with high spatial resolution over a wide area.

Here, we attempt to develop an image analysis technique for quantifying the debris abundance from 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 in the 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 later 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, areal coverage of marine debris on beaches are computed objectively, and thus, the estimated abundance of debris washed ashore on beaches can be used to, for instance, estimate the cost of beach clearance. Furthermore, we investigate what 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


Photo credit: Lightspeed Digital

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 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 m 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, which are described in Table 5-1. The debris rankings of aerial photographs were all spatially averaged based on those photographing locations along segments with the length of 1 km (Figure 5-1b). The debris ranking of segments can be viewed publicly on the website (http://www.arcgis.com/home/webmap/viewer.html?webmap=3c5fb88b7f3f4d97974615acad67af3e).

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

Debris Rating	Description
0 (unrated)	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 (more than 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

Image processing and subsequent analyses

In the present study, 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 is 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 follows:

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

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 the Equation (1) by applying a least square method; note that 10 unknown coefficients in Equation (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). 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 first determined 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 ($\overline{v}$) 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 $\overline{v} \pm s$, it can be determined as the debris pixel. In 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 to 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 headland, rocks, and trees that could be identified on both the satellite image and the aerial photograph were used as reference points. In the present study, five reference points (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 Clo-oose Beach located southwest in Vancouver Island on 28-29 July 2015 (Figure 5-1c). The dimensions of Cheewat and Clo-oose Beaches are approximately 98-m width × 1.9-km long and 49-m width × 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 such as plastics, beverage bottles, cans, disposable lighters, floats and lumbers was recorded, and the debris removed from the beaches. The surface number density was computed by using their number and area of each beach.

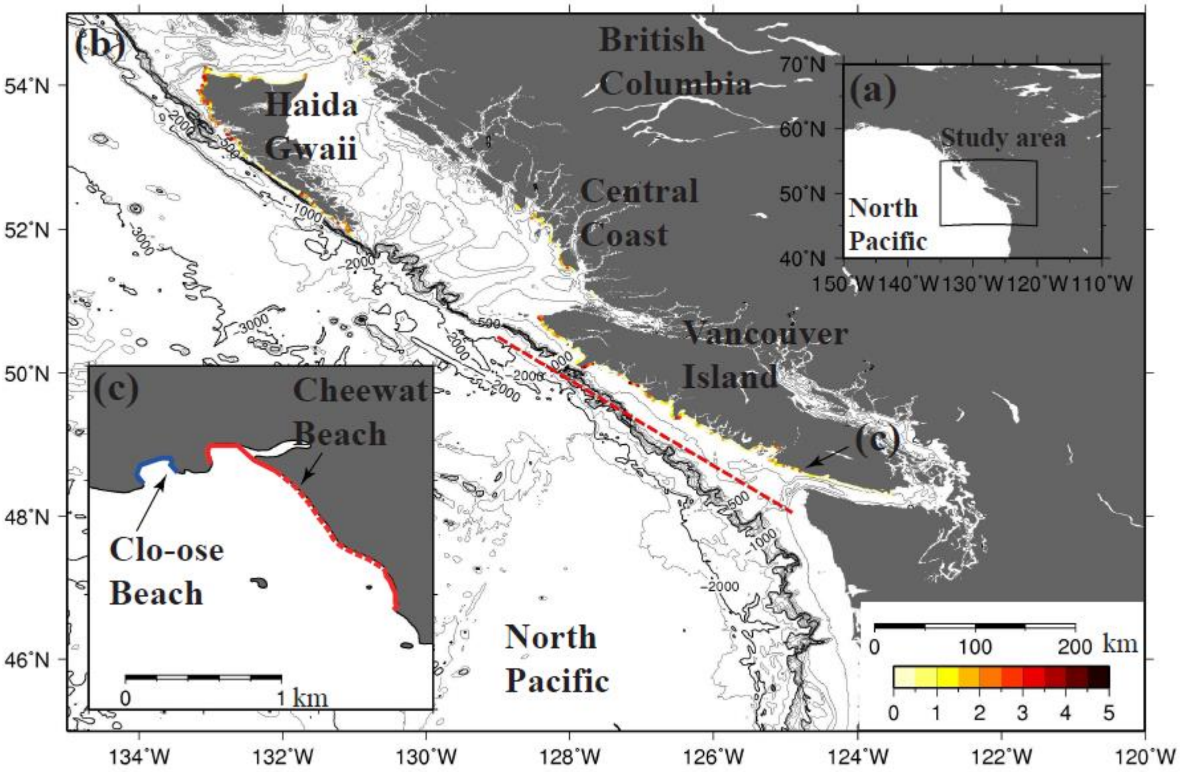

Figure 5-1. Study area. (a) Location of the west coast of British Columbia, Canada (box). (b) Enlarged map of the study area. The contour line denotes the isobaths in meters, and the red broken line is set for calculating the mean current/wind speed shown in Figure 5-5. The yellow-red gradation denotes 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 Clo-oose Beach and Cheewat Beach where the shoreline in-situ survey was conducted 28 July, 2015. The red (blue) boxes denote the coverage of the aerial photographs on Cheewat (Clo-oose) Beach where we estimated the percent covers.

Ocean current and sea wind data

To examine the factors that affect debris accumulation, we focused on the spatiotemporal variation of the ocean surface currents and sea winds west of the British Columbia coast (135°W–120°W and 45°N–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. In the present study, we used ocean current data calculated by the Hybrid Coordinate Ocean Model (HYCOM) and sea wind gridded data observed the Advanced Scatterometer (ASCAT). 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 provided here. The HYCOM provides us with a global daily current data with a grid spacing of 1/12° on native Mercator-curvilinear horizontal grid and 33 vertical levels from 19 September 2008 to the present. In the present study, the zonal (u) and meridional (v) current velocities in the uppermost layer ($z = 0.0$ m) downloaded via the website (http://hycom.org) were used. Kako et al. (2011) provided a global daily sea-wind vector data with a grid spacing of 1/4° by applying an optimum interpolation method to ASCAT data. These gridded ASCAT data were downloaded via the website: http://mepl1.riam.kyushu-u.ac.jp/~kako/ASCAT/NetCDF/.

Results

Validation of the percent cover estimated from aerial photographs

To compare the percent covers in the aerial photographs with the surface number densities observed by the in-situ surveys on Cheewat and Clo-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 the 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. This 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). In the present study, the outer boundary of the beach was determined in the processed image by visual examination (red outlines in Figure 5-2b). The accuracy of the projective transformation was approximately 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 photographs of the 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 Clo-oose Beach (Figure 5-2d, e, and f), and the resultant percent cover was 14%.

The percent covers estimated from the aerial photographs were consistent with surface number densities measured by the shoreline in-situ survey (Table 5-2). The percent cover on the Clo-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 northern and southern parts of the beach (red boxes in Figure 5-1c). Although we had taken eleven photographs of the Cheewat Beach in total, only three photographs were available for the projective transformation because of the lack of the appropriate five reference points in the remaining eight photographs. In general, reference points are difficult to put on sandy beaches because of the shoreline rapidly moving by tides and waves, unless immobile objects such as rocks are identified in the aerial photographs. The estimated percent cover of Clo-oose Beach is 14%, which is 3.5 times larger than that of Cheewat Beach (4%). It is found that the surface number densities on these two beaches were 0.049 and 0.014 items/m^2, respectively, of which ratio was also 3.5 times (Table 5-2). Hence, the estimate of percent covers would be reasonable to estimate the abundance of debris littered on the actual beaches.

Table 5-2. Comparison between the estimated percent covers and surface number densities on Clo-oose and Cheewat Beaches.

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

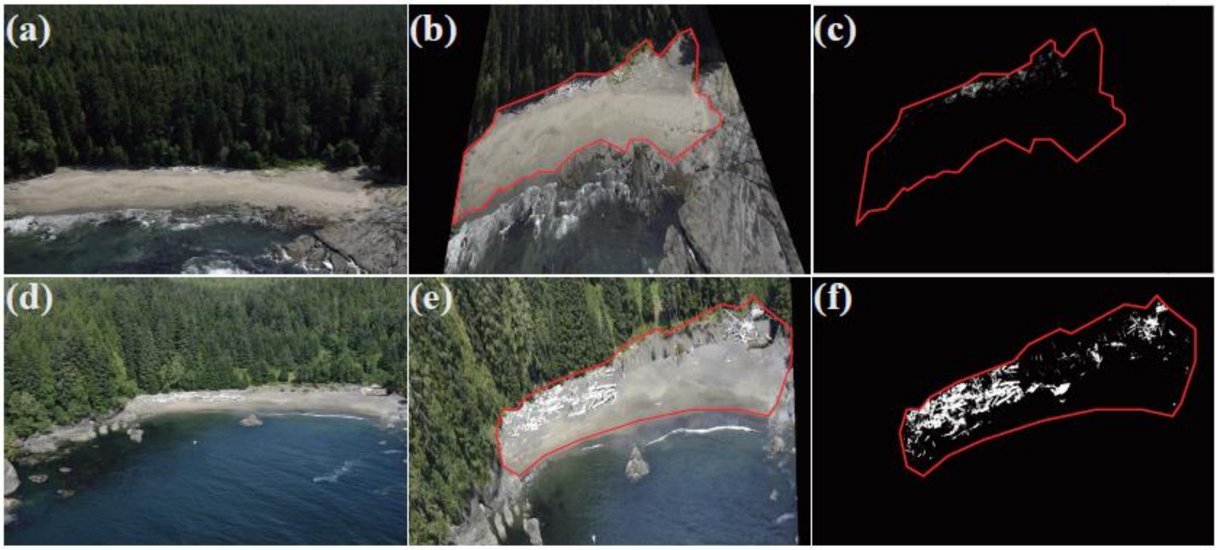

Figure 5-2. Image processing of photographs from Cheewat Beach (a, b, and c), and Clo-oose Beach (d, e, and f). (a) and (d): Original photographs taken by the aerial photographer. (b) and (e): The projective transformation method was applied to the images (a) and (d). (c) and (f): The pixels of marine debris shown by the white pixels were extracted by the image processing described in the text. The red outlines in the images (b), (c), (e) and (f) denote the beach areas defined to compute the percent cover.

Accumulation of marine debris on Vancouver Island

The debris ranking, shown in Figure 5-1b by color 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 both Haida Gwaii and Vancouver Island (Figure 5-1b). Among all aerial photographs of BC coasts, 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 ranking of percent covers estimated from 167 photographs (Figure 5-3) were approximately, but not exactly, the same as that of the debris ranking (Figure 1b). As shown in the debris-ranking map, the percent covers were estimated to be high in the northwest of Vancouver Island in comparison with the southeastern beaches. However, the highest percent cover of 38% was revealed around the northern tip of Vancouver Island, although the highest debris ranking (4-5) was found further south (Figure 5-1b). Relatively high debris-ranking (~3) was assigned around the Clo-oose and Cheewat Beaches (Figure 5-1c or (c) in Figure 5-1b) despite the moderate (<20%) percent cover in the same area (Figure 5-3). The across-shore directions (aspect) of beaches within each photograph are mostly southward (40%) or southwestward (45%) (Figure 5-4a). It is interesting note that, however, the percent covers averaged over beaches in each across-shore direction were nearly the same (8−10%) as far as the beaches with cross-shore direction from westward to southeastward (Figure 5-4b).

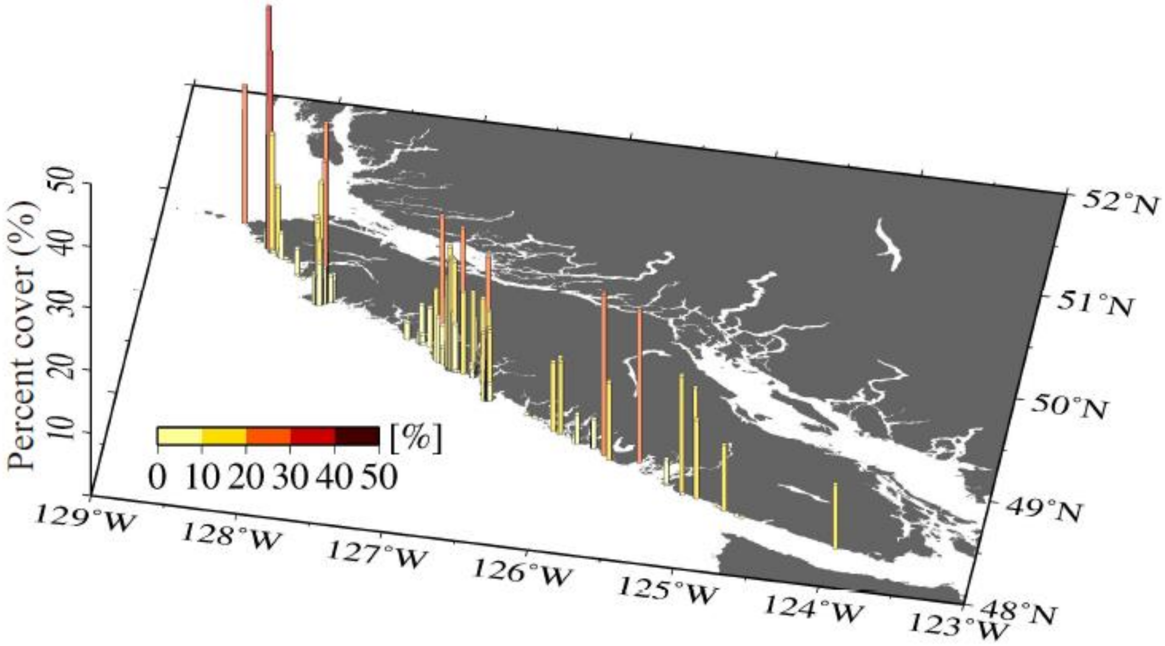

Figure 5-3. Horizontal distribution of percent covers estimated by applying our image processing to the aerial photographs taken in Vancouver Island. The yellow-red gradation represents the percent cover, of which color scale is shown in the lower left of the panel.

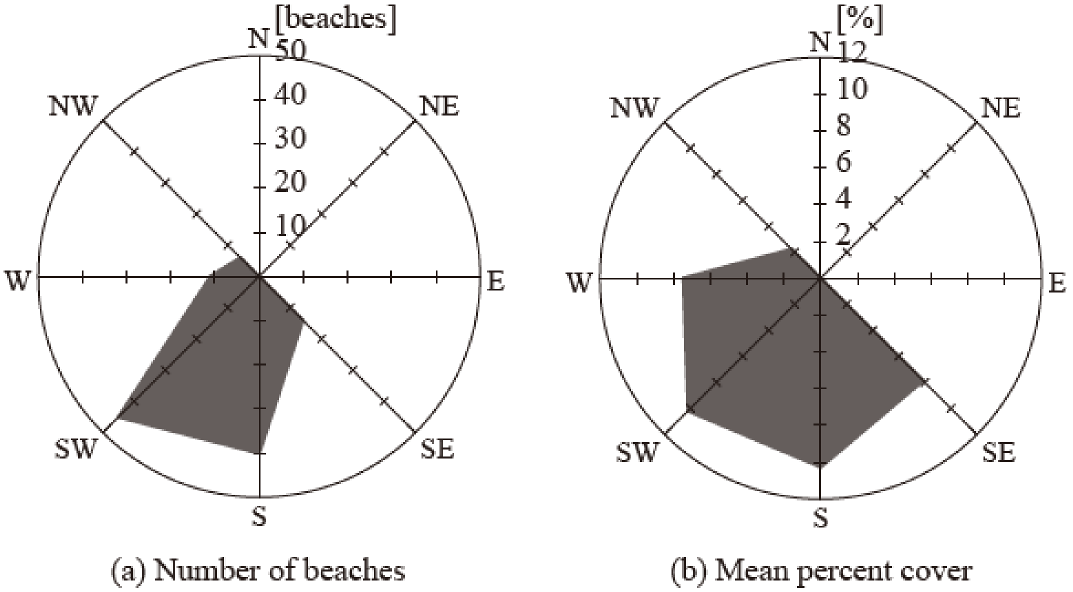

Figure 5-4. Frequency maps of (a) The number of beaches facing each direction, for which percent covers were calculated, and (b) The percent covers averaged over beaches in each across-shore direction.

Current and wind patterns off Vancouver Island

The dependence of debris abundance on both ocean currents and sea winds off Vancouver Island were likely to be significant, and thus, we investigated the spatiotemporal 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 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 have 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 be southeastward 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 was suggested.

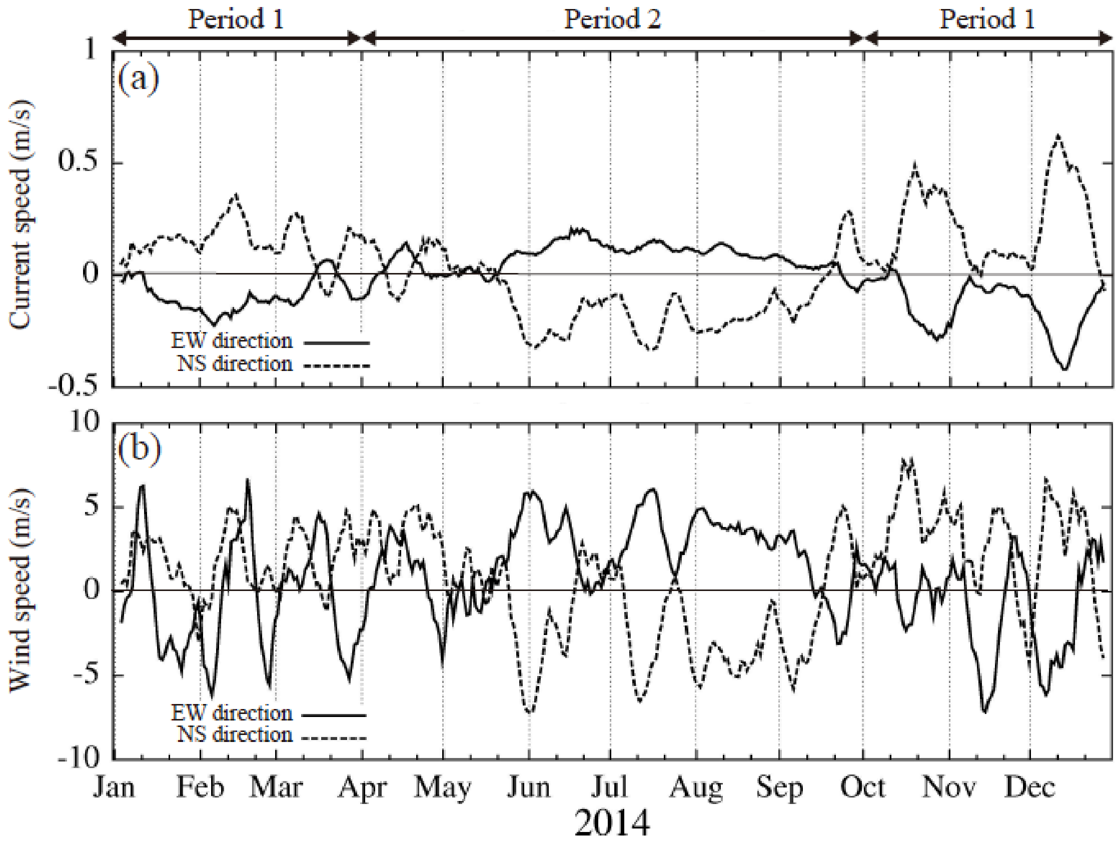

Figure 5-5. Time series of 7-day moving average of currents (a) and wind speeds (b) averaged over the red broken line in Figure 5-1b in 2014. In both panels, the solid and broken curves represent the time series of zonal (i.e., east-west) and meridional (i.e., north-south) components, respectively. The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

The current fields averaged over period 1 (Figure 5-6a) revealed 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 was consistent with Mysak (1983), where an annual cycle of the California Current System was described on the basis of the current-meter moorings. The wind fields averaged in each period (Figure 5-6c and d) demonstrated 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 the period 1 and 2, respectively. The surface currents over the offshore area were directed toward the coast during period 1 (Figure 5-6a), while the offshore currents in period 2 were directed offshore-ward (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.

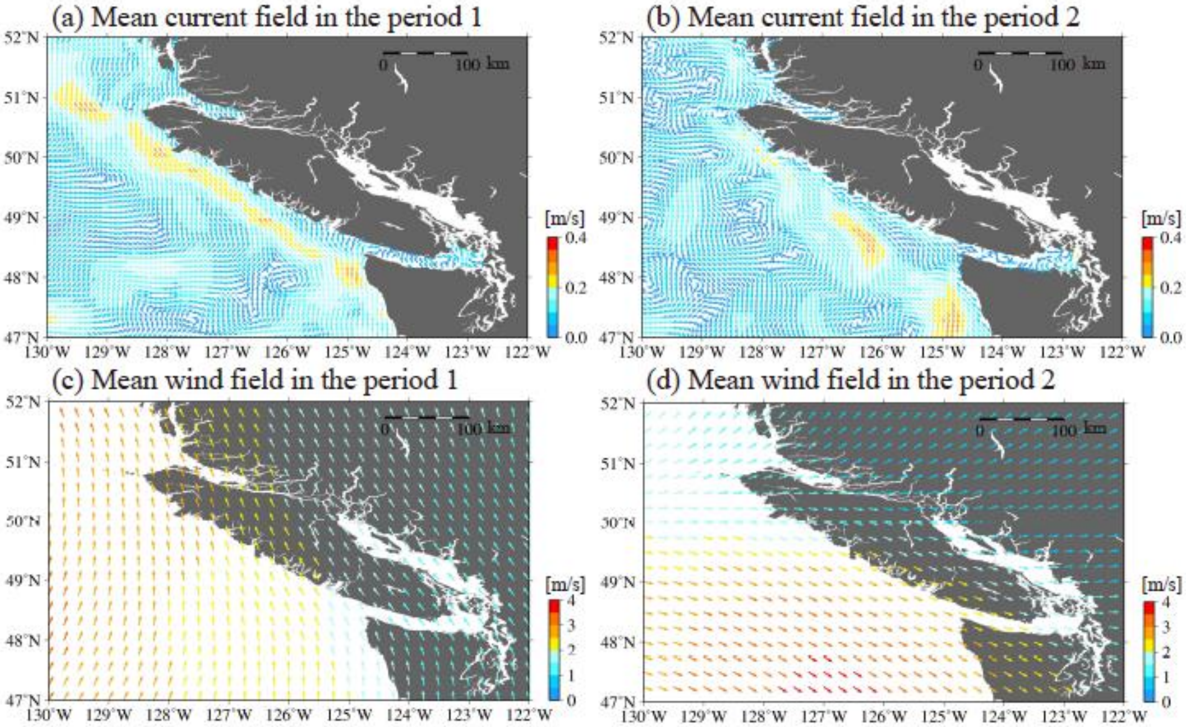

Figure 5-6. Sea surface current (a, b) and wind (c, d) vector fields during period 1 (fall and winter; left panels) and period 2 (spring and summer; right panels). The color scales of current and wind speeds are shown on the right of each panel.

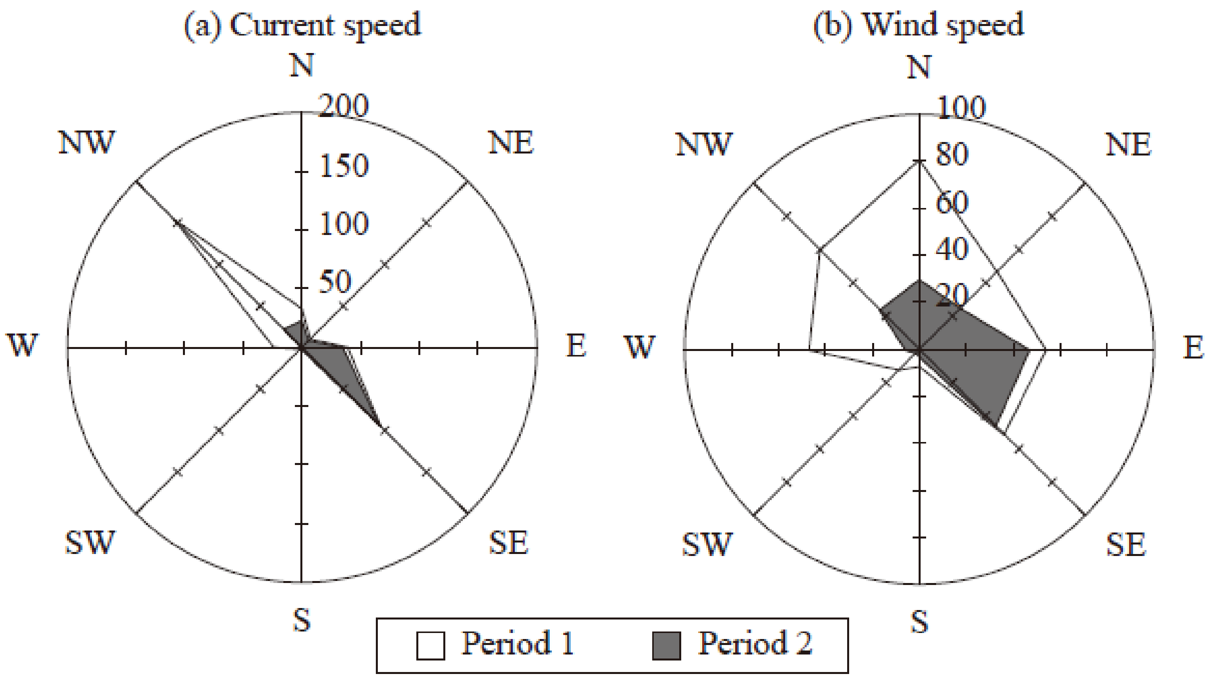

Figure 5-7. Current (a) and wind (b) roses using data averaged over the red broken line in Figure 5-1b after smoothing by the 7-day moving average. The frequency of each direction during 2014 was depicted with the bold solid line. The white (stippled) area indicates the frequencies of current/wind during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

Discussion

Relationship between debris accumulation and current and wind patterns

Almost all beaches in Vancouver Island face southwest and south (Figure 5-4a), and thus, the northeastward and northward (i.e., onshore-ward) motion of marine debris are favorable for washing ashore. We next considered the contributions of ocean currents, wind waves (hence, Stokes drift), and sea winds (hence, leeway drift) on the onshore-ward 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 southwest-facing and south-facing beaches dominant in 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 was 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., onshore-ward) winds were intensified in period 1 (Figure 5-7b). The marine debris would be efficiently transported onto the south-facing and southwest-facing beaches dominant in Vancouver Island (Figure 5-4a) owing to the leeway drift associated with these onshore-ward sea winds. The contribution of winds, irrespective of their direction, was likely especially important in period 1, because the frequency distribution of percent cover (Figure 5-4b) for that period seemed approximately (not exactly) to be a "mirror image" of that of the wind directions (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 onshore-ward winds, although additional field surveys such as drifter experiments are required for the contribution of the Stokes drift to be conclusive.

The marine debris washed onshore was more likely to occur in period 1 (fall and winter). This was because the favorable conditions for onshore Ekman flows (Figure 5-6a) and onshore-ward winds (hence, leeway and Stokes drift; Figure 5-7b) appear in this season. The relative importance among these three causes remains unknown in the present study. However, Isobe et al. (see Chapter 4) investigated the time series of debris abundance, winds, and ocean currents concurrently to elucidate relative importance. The predominance of marine debris in period 1 was consistent with the spatial distribution of percent cover (Figure 5-3). The northward winds in period 1 were 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-facing and northwest-facing beaches, although the number of these beaches was very low in this region (Figure 5-4a). Also, onshore-ward winds occurring in period 2 (Figure 5-7b) acted to increase marine debris on the beaches although the frequency was smaller than that of period 1.

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 adverse impacts of marine debris on marine ecosystems and resources, we need to carefully select these sites when these activities are conducted, because the effectiveness of these activities is likely to highly depend on appropriate site choice. It is difficult to conduct these activities concurrently on multiple beaches because of the limitation of human and financial resources. The present study suggests that the current and wind patterns in the offshore region of the study fields 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 limitations. In the present study, we were unable to compute the percent covers from the eight aerial photographs on the Cheewat Beach because of the lack of the appropriate five reference points within the photographs. First, only the aerial photographs taken on beaches with identifiable land features (e.g., large rocks) could be selected to apply our image processing, whilst the projective transformation was incapable of processing aerial photographs of beaches without immobile objects (e.g., sandy beaches). Second, the debris abundance only at the surface of beaches can be evaluated by the aerial photographs. Hence, the debris abundance may be underestimated in comparison with the true abundance measured by the in-situ survey of beaches where marine debris washed ashore for a long time is deeply "stratified" within a relatively narrow area. Nonetheless, it should be emphasized that aerial photographic surveys have an advantage in monitoring the marine-debris abundance over broad areas, especially when in-situ surveys on the beaches are prevented because of remoteness or inaccessibility.

Our aerial photograph image processing has an extra advantage regarding the "re-analysis" of archived aerial photographs of marine debris in the past. The projective transformation method can be applied to archived photographs by setting four referencing points, at least, within the photographs using the satellite visual images provided by Google Earth. The Alaska Department of Environmental Conservation, for instance, has also conducted the aerial photographic surveys to monitor JTMD potentially washed ashore along the south coast of Alaska. The aerial photographs with accompanying debris rankings (Table 5-1) are publicly available on their website (http://www.arcgis.com/home/webmap/viewer.html?useExisting=1&layers=555996dd72e84b6c9fa2952692fe85d2). Applying the image processing techniques of the present study to these archived aerial photographs may be used to further investigate the spatiotemporal variability of marine debris, including JTMD, over broad areas. Recently, ortho-imagery surveys (aerial photography taken orthogonally to the ground) were conducted for

Photo credit: Alaska Department of Environmental Conservation marine debris on the main Hawaiian Islands (see Chapter 6). The advantage of their procedure is that areas covered by marine debris can be directly computed from the photographs without additional georeferencing. Meanwhile, the advantage of the present study is that our procedure is applicable to photographs taken obliquely from airplanes as in the conventional manner, resulting in a cost reduction of one order of magnitude over ortho-imagery surveys.

Conclusions

We have developed an image analysis technique to quantify the marine-debris 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 beach covered by aerial photography, was adopted to indicate debris abundance. The percent cover was validated through comparison with the amount of marine debris per unit area (surface number density) measured by the shoreline in-situ surveys on two beaches of Vancouver Island (i.e., Clo-oose and Cheewat Beaches). The relative amount of marine debris measured by the aerial survey for the two beaches was consistent with the surface number densities measured in situ. Marine debris tended to have higher accumulation in the northwest of Vancouver Island than the southeast. In addition, the horizontal distribution of percent covers 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 became 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 is capable of processing archived aerial photographs, even if the physical reference points were not predetermined. Therefore, in-depth examination using the archived aerial photographs can provide additional information about the places and time periods with higher debris accumulation and arrival of JTMD which gradually increased since 2011.

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THEME II – Arrival of Debris

Chapter 6: Surveillance of debris in the Hawai’ian islands

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Abstract

Aerial surveys of the eight main Hawaiian Islands (MHI) 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 15% each, Oahu with the lowest at just 5% statewide.

In total, the project counted over 20,000 individual items of debris. Plastics were overwhelmingly the dominant debris type by category, accounting for 80% of total debris. Vessels, metal, cloth, tire, processed wood, foam, and unknown debris types made up the remaining 20% combined. This project provided a baseline of marine debris densities at a moment in time, and 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 project arranged for all 52 vessels to be further scrutinized through in situ evaluations and determined that only 27 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 study of marine debris cleanup events that occurred prior to the flyover dates for each island. The project received removal data from over 20 federal, state, city, and county, and private groups totaling more than 2000 cleanups. This effort represented at least 70 metric tons of debris removed and well over 30,000 manhours. The time elapsed between flights and cleanup dates was used to evaluate any potential impact of debris removals 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 project was to prepare a public resource to share the study’s findings. This data is

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 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 plan further management actions and evaluate marine debris accumulation patterns in Hawaiʻi.


Photo credit: Lightspeed Digital

The objective of this project was to document and describe marine debris on coastlines of the MHI through high-resolution aerial imagery paired with ArcGIS mapping software to locate, quantify, and categorize debris accumulations. Additionally, the project aimed to disburse and distribute its findings through peer-reviewed journal publication, presentations, conferences, and online resources.

Methods

The project 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 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 Hawaiʻi (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 above ground level to achieve a ground resolution of two centimeters per pixel and a swath width between 200-300 meters. 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 five meters root mean square (RMS), then divided into GeoTIFF raster tiles for use in ArcGIS.

Imagery analysis for debris composition, density, and distribution

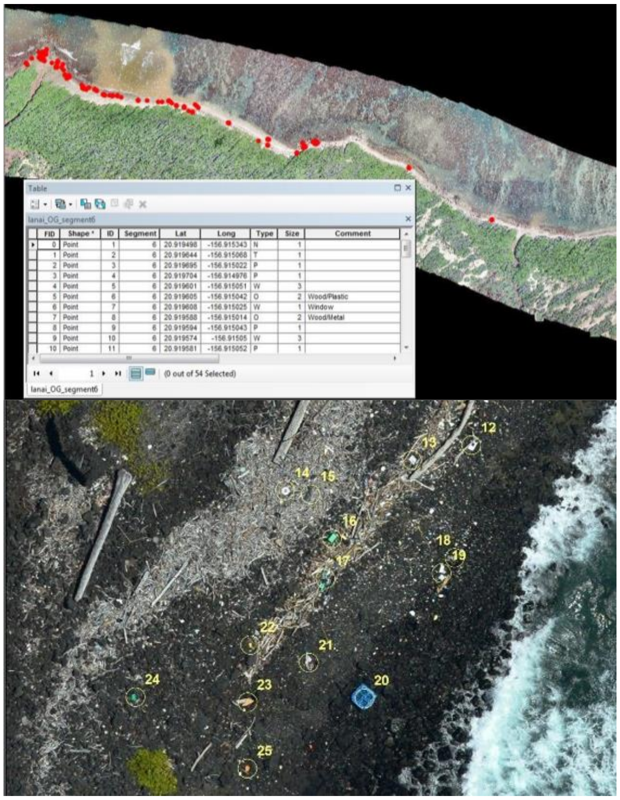
Marine debris type was classified into seven categories (Table 6-1) prior to GIS analysis. While there were limitations on the ability to determine debris types at this scale, categorization of identifiable debris was useful to determine trends in debris accumulation. If a piece of debris was made up of more than one type of material, the main material was listed and the additional materials were included as a comment. Debris was also categorized into 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.

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

Material	Description
Plastic	Any items made from plastics 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

Line shapefiles divided each island'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 6-1).

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-kilometer lengths to improve the visual usefulness of the statewide accumulation map at the required scale.



FID	Shape *	ID	Segment	Lat	Long	Type	Size	Comment
0	Point	1	6	20.919498	-156.915343	N	1	
1	Point	2	6	20.919644	-156.915068	T	1	
2	Point	3	6	20.919695	-156.915022	P	1	
3	Point	4	6	20.919704	-156.914976	P	1	
4	Point	5	6	20.919601	-156.915051	W	3	
5	Point	6	6	20.919605	-156.915042	O	2	Wood/Plastic
6	Point	7	6	20.919608	-156.915025	W	1	Window
7	Point	8	6	20.919588	-156.915014	O	2	Wood/Metal
8	Point	9	6	20.919594	-156.915043	P	1	
9	Point	10	6	20.919574	-156.91505	W	3	
10	Point	11	6	20.919581	-156.915052	P	1	

Figure 6-1. A swath of Kaua'i coastline in ArcGIS and the data table of the identified dots of debris (left), with a zoomed screenshot of identified marine debris with numbers on Kamilo Point, Hawaii Island (right).

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

The project recognized two shortcomings to the aerial imagery analysis: 1) the resolution wasn't 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 project, we attempted to address these deficiencies.

All debris items detected and categorized as vessel were inspected to verify their status as marine debris. Each vessel’s position relative to the high water mark, location, condition, and description were measured in situ. Additionally, the project used historical imagery from Google Earth 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 6-2).

Figure 6-2. JTMD vessels detected in the aerial imagery (top) and their corresponding *in situ* photo (bottom).

For beach cleanups, the project contacted over 50 community members, federal, state, and local organizations, and received over 2000 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 project approximated the coordinates. Events that only addressed litter or did not occur on coastlines were discarded.

Results

The project analyzed the data for each of the eight islands (DLNR report http://dlnr.hawaii.gov/dar/reports/). Marine debris was heavily concentrated on the island of Niihau. Niihau contained 38% of the total debris identified across all of the islands surveyed. All other islands contained 14% or less of the total debris identified, with Oahu being the least dense, containing only 5% of the total debris. Debris density was not reflective of coastline length or number of segments (Figure 6-4). On all islands, marine debris was primarily concentrated on north and east-facing shores, with west-facing shores containing the least amount of debris (Figure 6-3).

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 islands 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 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 5% to 21% (average 11%) for derelict fishing gear. As the vast majority of buoys, floats, 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.


Photo credit: Lightspeed Digital

The size class distribution of identified debris was far more unanimous across all islands. The "very small" category (< 0.5 m^2) made up 86% of the total debris found on all islands, and contributed 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.

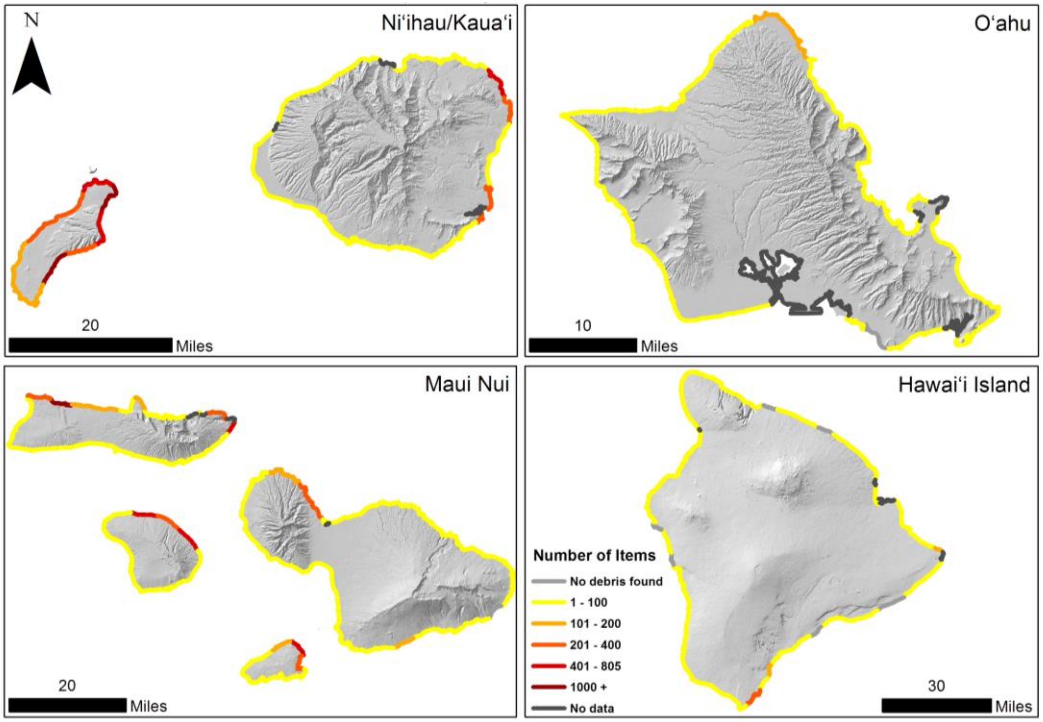


Figure 6-3. Density and distribution of debris on the MHI showing marine debris “hotspots,” segments with 100 or more items. Segments were divided into 8 km lengths to improve visual interpretability.

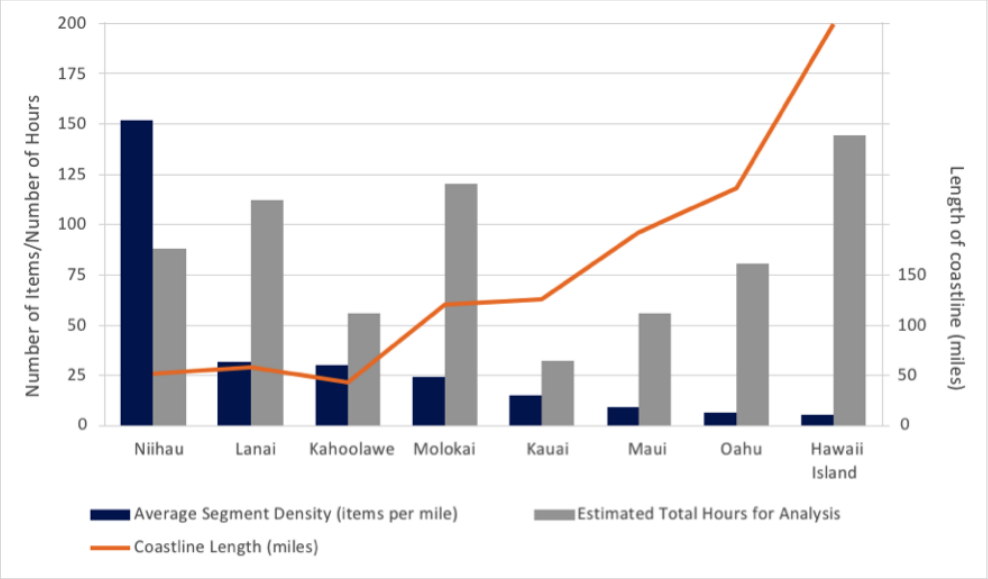


Figure 6-4. Average number of debris items found per 1-mile segment of coastline for the MHI, in relation to total coastline length in miles.

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, only 27 were determined to be ADVs. Of those 27, the project 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 was 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 was compiled to evaluate the potential influence of removals on shoreline density ratings. 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 occurred 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 sixteen cleanups that occurred on ten 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 occurred 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 6-5).

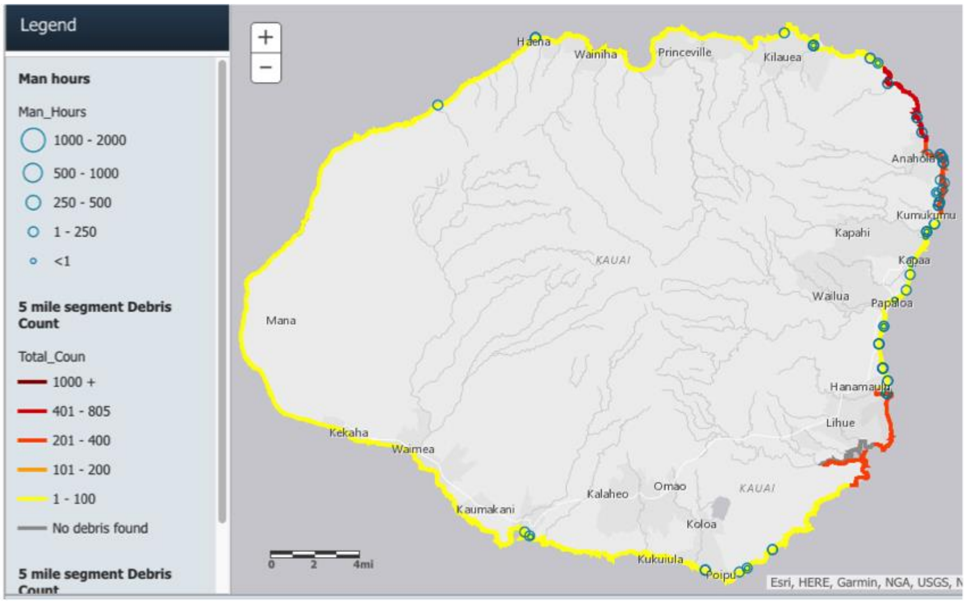


Figure 6-5. Sample screenshot of Kauai showings how man-hours were mapped over segment ratings.

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 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 (Pacific Islands Fisheries Science Center [PIFSC], NOAA 2010). Similarly, an Alaska survey collected and analyzed geotagged photos but without mosaicking. This process of locating debris is more tedious and less reliable. 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 these 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 (Blickley et al. 2016; PIFSC 2010). These factors may also explain why Niihau, the northernmost main Hawaiian island, had 38% of all debris in the state and all other islands 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 of 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 & Ryan 1997; Martin and Sobral 2011; Moret-Ferguson et al. 2010) 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 & 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 (Barboza 2015; Derraik 2002; Gall & Thompson 2015; Vegter et al. 2014). 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.


Photo credit: Lightspeed Digital

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, personal communication). In 2015, ten vessels were reported to DLNR. The aerial surveys increased detection by nearly twofold, 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 six months of initially being detected on shore. Detecting 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 1000 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 project's partner Resource Mapping Hawaii. All flights had to be scheduled in as small 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 project with the chosen method of a snapshot accumulation study. Seasonal variation and change over time couldn't be measured with a single set of flyovers, but it did provide a baseline for future accumulation studies. The project 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 project, 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 will enter into a new data-sharing endeavor to increase transparency and coordination to cleanup efforts throughout the MHI.

The project 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 project to all cleanups in the MHI since 2004. This PICES 'Assessing the Debris-Related Impact from Tsunami' (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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THEME III – Rafting of Japanese Species

Chapter 7: Characterization of the invertebrate biodiversity arriving with Japanese Tsunami Marine Debris in North America and the Hawaiian Islands

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Abstract

More than 650 objects related to the Great 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, and many other items associated with Tohoku coastal communities, Japanese trees, docks, and post-and-beam wood. Object arrival over time demonstrated a relatively consistent pattern of spring pulse landings. Nearly 400 species of Japanese marine animals and plants (including about 320 species of marine invertebrates) have been detected on the debris field arriving since the summer of 2012. Remarkably, at least four new species of marine life have been detected on Japanese tsunami marine debris (JTMD). Invertebrate diversity was dominated by six groups: bryozoans (moss animals), bivalves (mussels, scallops, oysters, clams, and shipworms), polychaetes (marine worms), hydroids, gastropods (shelled snails and nudibranchs), and sponges. The first three groups composed over 40% of the diversity; all six groups combined accounted for nearly two-thirds of the diversity. Cumulative species richness mirrored the annual debris arrivals in spring, resulting in staircase-like pulses. Twelve invertebrate species occurred on 35 or more objects. More than 40% of all objects transported the large marine Mediterranean mussel *Mytilus galloprovincialis*, a 20th century invasion into Japanese waters. The Western Pacific bryozoan *Scruparia ambigua*, was very common and occurred on one-third of all objects, followed by the large Asian rose barnacle *Megabalanus rosa*. Two-thirds of the most common species were bivalves, bryozoans, or barnacles. No fewer than 109 species, or 40% of the total macro-invertebrate and fish diversity, were found only once. Eight objects with more than three unique species aboard accounted for half of these species alone, or approximately 20% of the biota; an additional 45 objects, each with 1 or 2 unique species, accounted for the remaining presence of "one-off" occurrences. The number (40) of species arriving dead was surprisingly few, given the length and time duration of

the voyages across what was considered to be a largely hostile open ocean environment for coastal species.


Photo credit: Ocean Legacy

Adding to the expectation that a subset of the marine fauna and flora 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 as the debris drifted into more southern waters. The number of southern species appearing on JTMD more than doubled between 2012 (3 species), 2013 (10 species), and 2014 and later (24 species), suggesting that the debris continued to take a wider and longer circuitous path through lower latitudes over time. Remarkably, JTMD with living Japanese species from the Tohoku coast continues to arrive in North America and the Hawaiian Islands, as we approach the close of Year 6 of the JTMD phenomenon.

Introduction

The purpose of the biodiversity portion of the ADRIFT (Assessing the Debris-Related Impact From Tsunami) project was to attempt to assess the overall diversity of the invertebrate and fish fauna associated with the debris field generated by the Great East Japan Earthquake and Tsunami that occurred March 11, 2011, which subsequently rafted, over the ensuing years, to the Hawaiian Islands and to North America. Our objectives were to obtain the widest variety of biological samples over time and space as feasible and practicable; to process and sort these as assiduously and efficiently as possible to the lowest possible taxonomic level, to permit identification either in the laboratory or by sending specimens to specialized taxonomists; to continue identifications in our laboratory and extract identifications from taxonomists in order to populate a Japanese tsunami marine debris (JTMD) biodiversity database, and to analyze the data for diversity patterns over time and space. A corollary effort was focused on providing provide bivalve mollusk samples (particularly *Mytilus galloprovincialis*) for parasite analysis and fresh tissue samples, where and when possible, for potential genetic analyses (see Chapter 10).

Methods

Sample acquisition and processing

Early on, 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 established in co-operation 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 of marine invertebrates 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. As noted, when appropriate, selected samples were then prepared and forwarded to laboratories in Moss Landing Marine Labs (MLML, Geller) and the Smithsonian Environmental Research Center (SERC, Ruiz).

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 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, more than 60 taxonomists in Australia, United States, Canada, Germany, Japan, Norway, Russia, Singapore, and Taiwan were engaged (Appendix 7-2).

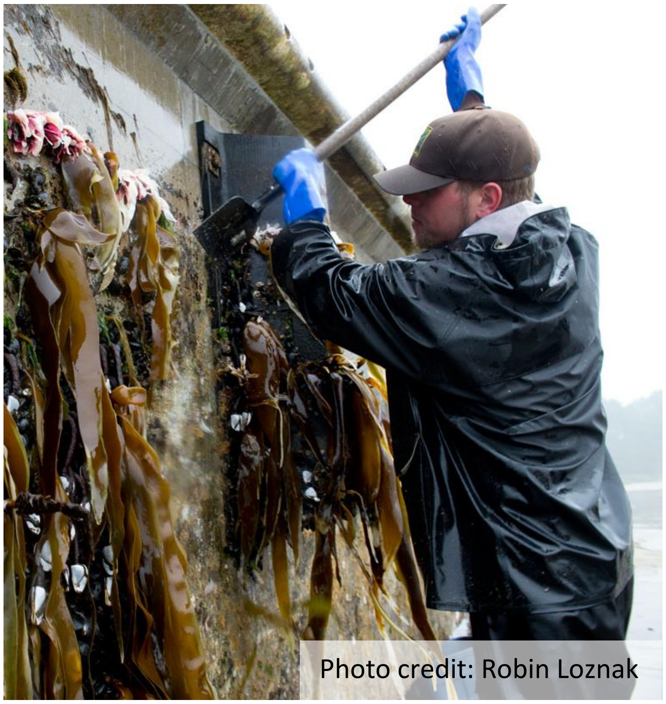


Photo credit: Robin Loznak

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 more than 650 items registered and analyzed, we judged 107 (as of January 2017) 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 "*Category 1*" objects (Appendix 7-1, last column). 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, the volume and quality of sample received, and similar criteria. The biodiversity on these 107 objects were 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.

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, which data could then be provided to the Japanese Consulate and formally confirmed.
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 bear 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 occasional 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 and on, and characterized by subsequent slowing in item arrivals as the debris field entered its 4th, 5th, and 6th years. If debris were arriving independently and steadily 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 -- since 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 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. Vessels: Finally, 100% of all objects -- vessels or otherwise -- intercepted in Hawaii or North America since 2012, thought to be from Japan and that 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.

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 these were frequently present on JTMD objects and also are known to have a diverse range of parasites, pathogens, and commensals (hereafter parasites) worldwide, including the hydroid *Eutima* that was detected previously on JTMD (Calder et al. 2014).

We sampled and tested 1,158 mussels from JTMD objects for the presence of parasites, combining previous work funded by the National Science Foundation with the PICES 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, tissue samples were obtained and sent to MLML for genetic identification of the mussels. 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, only mussels collected from four JTMD objects (JTMD-BF1; JTMD-BF-6; JTMD-BF-8; and JTMD-BF-23) 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 n=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, CA) 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 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 ~350bp of one variable region of the small subunity of ribosomal RBA (SSU) gene and is capable of amplifying multiple genera (*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 Drs. Ryan Carnegie for *Marteilia refrigens* (Virginia Institute of Marine Science) and our own collection for *Perkinsus* species and haplosporidians.

Resulting sequences were edited using Sequencher 5.1 (Gene Codes Corporation, Ann Arbor, MI). To initially determine the organism detected, all sequences were subjected to a nucleotide search using BLAST (http://blast.ncbi.nlm.nih.gov/) in GenBank against the nr 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 (http://www.ncbi.nlm.nih.gov/).

Results

JTMD objects analyzed

To date, 653 objects have been registered and analyzed in whole or in part for the marine life attached to these objects (Appendix 7-1; 677 items bear numbers, but 24 have been deleted over time for a number of reasons). All objects examined were from Alaska, British Columbia, Washington, Oregon, California, the Hawaiian Islands, and Midway Atoll. Most objects 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 2 large docks from Misawa in Aomori Prefecture (Figure 7-1).

Photo credit: Nikolai Maximenko

More than 70 vessels were sampled that were derived from the tsunami strike zone (including Aomori, Iwate, Miyagi, and Fukushima Prefectures). Of some 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 "Category 1," as detailed in Methods above.

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 (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. Surprisingly, despite the extensive studies of shipworms in the 20th century in the North Pacific Ocean, one new species, native to Asia, was detected (Table 7-1). 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 Northeast Pacific for some 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 continue to arrive as of December 2016.

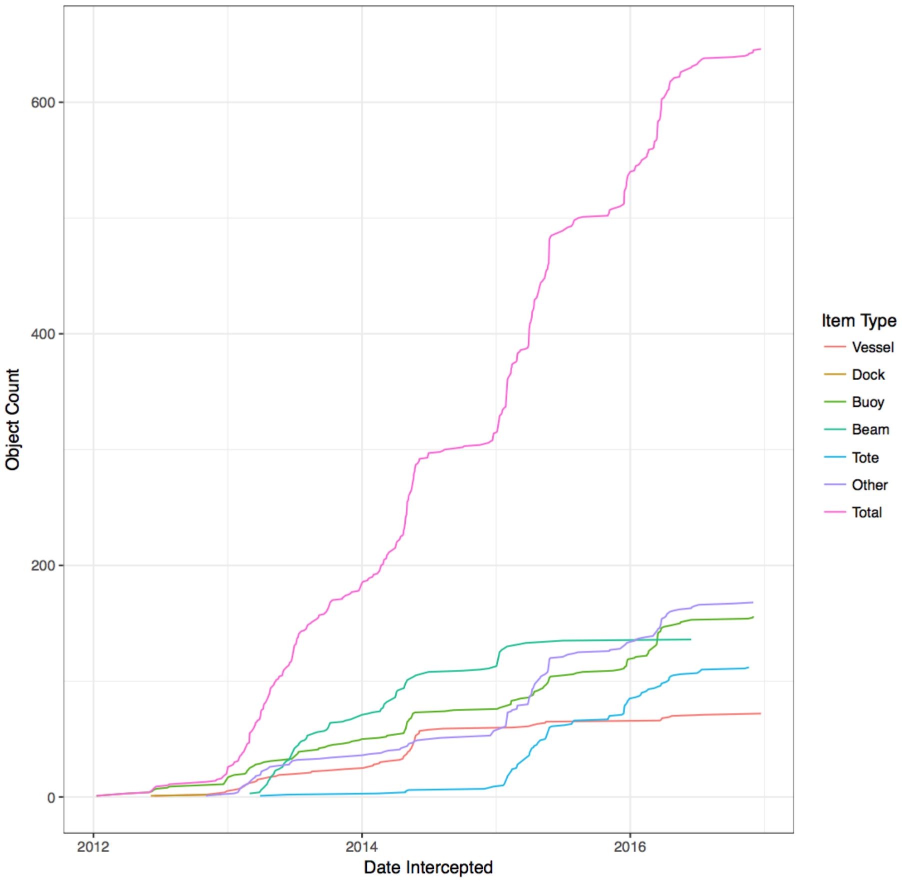
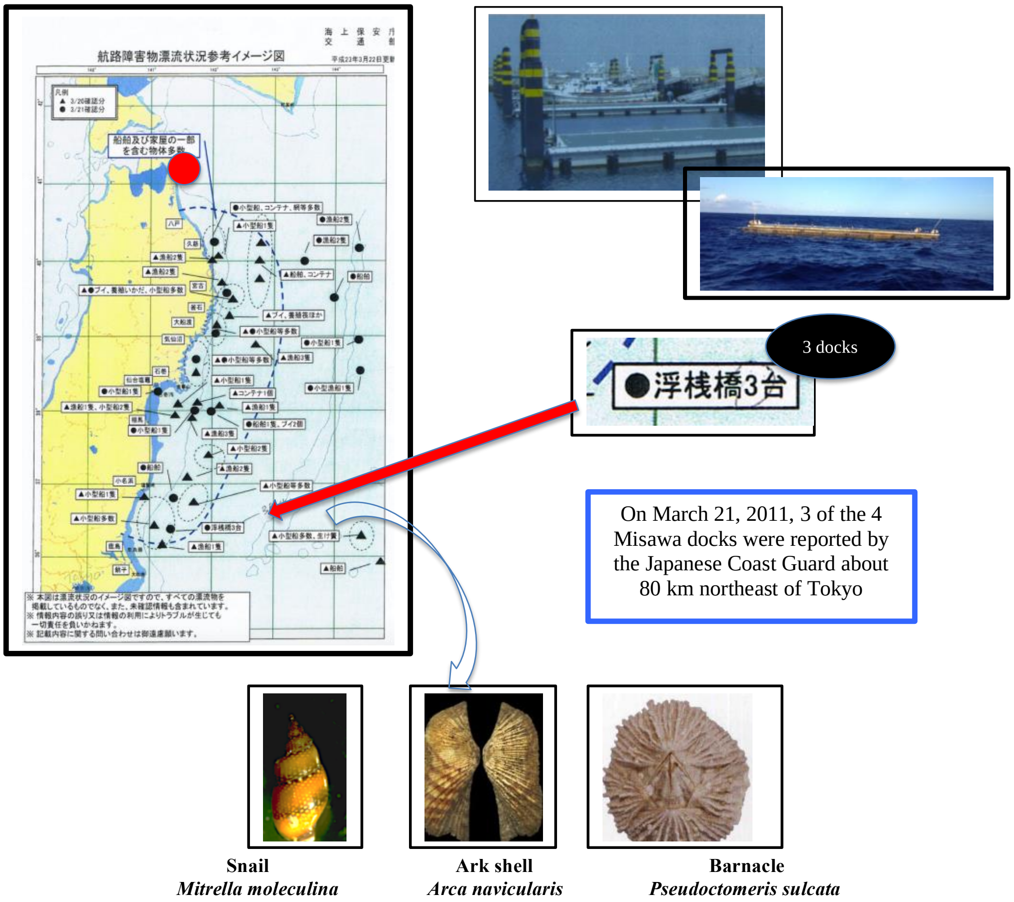


Figure 7-1. Cumulative JTMD object arrival over time.

The two Port of Misawa docks that arrived on the 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, USA, 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.



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 three 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* and the ark clam *Arca navicularis*. Misawa 3 landed in Washington on December 18, 2012 with the southern barnacle *Pseudoctomeris sulcata*. *Arca navicularis* was to arrive a number of times over subsequent years; *Mitrella moleculina* and *Pseudoctomeris sulcata* did not appear again. All three species were acquired at around 35° N latitude or further south.

Mitrella	OSU website
Arca	http://www.idscaro.net/sci/01_coll/plates/bival/pl_arcidae_1.htm
Pseudoctomeris	Yamaguchi and Hisatsune, 2006, Sessile Organisms 23: 1-15.

Figure 7-2. Acquisition of southern species by Misawa 1 (JTMD-BF-1) and Misawa 3 (JTMD-BF-8) before departure to north Pacific.

JTMD biodiversity assessment

Nearly 400 Japanese species of marine animals and plants have been detected on the debris field arriving in the Central and Eastern Pacific Ocean since the summer of 2012. These include approximately 320 species of marine invertebrates and "protists" (including foraminiferans and ciliates) (Appendix 7-3) and approximately 80 species of algae, or seaweeds (see Chapter 9). As noted above in Methods, more than 60 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* and amphipods in the genus *Jassa*. In addition, auxiliary genetic studies provided genetic insights into the origin of the debris itself.

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 84 macro-invertebrate species; Misawa 3 arrived with 15 additional species not found on Misawa 1. Thus, Misawa 1 and Misawa 3 together arrived with approximately 100 species, or nearly one-third of the total biota that arrived between 2012 and 2016. Twenty-one species never seen again on any additional objects (see "Unique Species," below) arrived on Misawa 1; three additional species, also never seen in subsequent years on arriving debris, occurred on Misawa 3, for a total of 24 species that were unique to these first two large items in 2012. The acquisition of a faint southern biological signature by both docks is discussed below.

Remarkably, at least four new species of marine life have been detected on JTMD (Table 7-1), which have been or are in the process of being described.

Table 7-1. New species of marine life detected on Japanese tsunami marine debris (JTMD).

New species	**Description and status**
Shipworm – *Psiloteredo* new species	The shipworm *Psiloteredo* new species (Mollusca: Bivalvia: Teredinidae) appeared in the first waves of post-and-beam and other woody debris arriving in the Pacific Northwest in the summer of 2013. It is a relative to a North Atlantic species, *Psiloteredo megotara*. A description of this new species, native to the North Western Pacific, is in preparation. Psiloteredo has proven to be one of the most common, and the largest, shipworm in JTMD woody debris, forming distinctive laminations inside its burrows, making wood biodeteriorated by this species particularly distinctive.
Bryozoan – *Bugula* new species	The bryozoan, or moss animal *Bugula* new species (Bryozoa: Cheilostomatida: Bugulidae) was first detected on a vessel that landed on Gleneden Beach, Oregon in February 2013. It has continued to appear on more than 35 objects through 2016. Native to the North Western Pacific, it has been named and will be part of the series of papers noted below scheduled for Aquatic Invasions.
Red algae – *Tsunamia transpacifica*	The new red seaweed species *Tsunamia transpacifica* was found on a wide variety of plastic debris washing ashore in Washington and Oregon. Its natural habitat is unknown, but it may be a member of the oceanic neustonic guild of the North Pacific (West et al. 2016).
Red algae – Stylonematophyceae new species	A second new species of red algae in the class Stylonematophyceae was also detected, but has not been described.

Parasites in JTMD mussels

We detected the parasitic hydroid *Eutima* sp. 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 detected on objects arriving to Oregon and Washington. No positive cases of the other two macroparasites, including pinnotherid crabs and the copeopod *Mytilicola orientalis*, were detected among the 1,158 mussels screened to date.

Eight mussels (3%) tested positive for haplosporidians on JTMD, of the 264 mussels screened to date. These were on JTMD objects that arrived to 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 *Mareilia* sp.

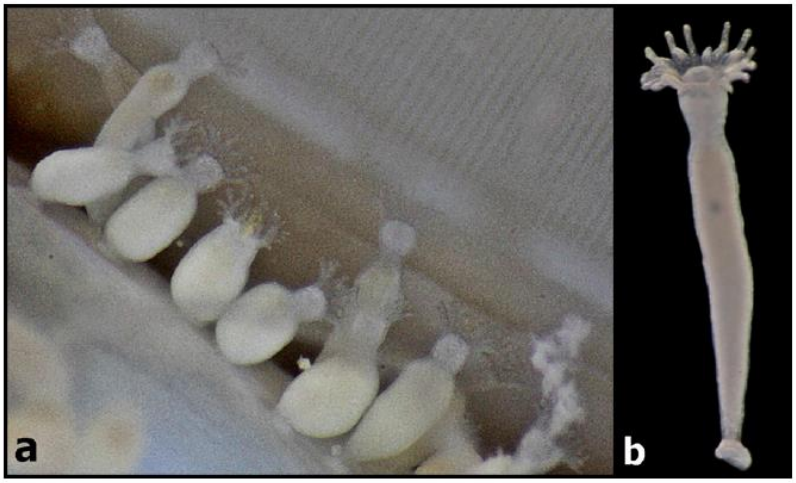


Figure 7-3. Pictures of the hydroid *Eutima* sp. from the inside of a mussel, collected from JTMD arriving to North America. Image from Calder et al. (2014).

Macro-invertebrate biodiversity

Six groups dominated invertebrate diversity (Table 7-2, Figure 7-4): bryozoans (moss animals), bivalves (mussels, scallops, oysters, clams, and shipworms), polychaetes (marine worms), hydroids, gastropods (shelled snails and nudibranchs), and sponges. The first three groups comprised over 40% of the diversity; all six groups combined accounted for nearly two-thirds of the observed diversity (Table 7-2). In Figure 7-3, Annelida were primarily polychaetes, with the inclusion of rare oligochaetes, and Cnidaria included seven species of sea anemones and corals.

Table 7-2. Overview of JTMD taxa and biodiversity.

Group	**Species (n)**
Rhizaria (including foraminifera)	14
Ciliophora	6
Invertebrates	296
Bryozoa	49
Bivalvia	46
Polychaeta	45
Hydrozoa	26
Gastropoda	20
Porifera	18
Fish	2
Total species	318
Invertebrates + Fish	298
Invertebrate microbiota (nematodes, platyhelminthes, copepods, ostracods, acarina)	31
Total for Macro-Invertebrate analyses	267

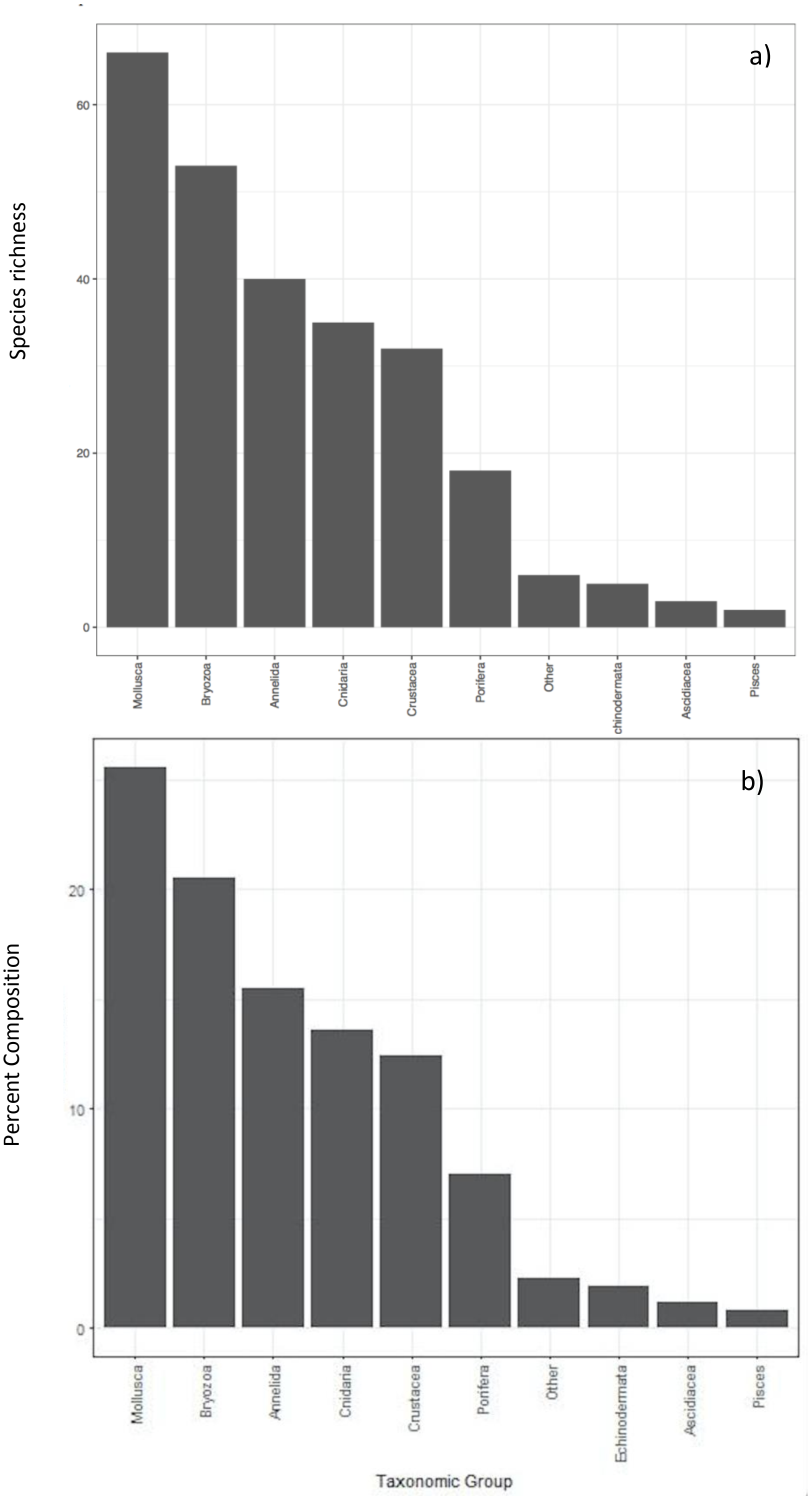


Figure 7-4. JTMD biodiversity by a) richness taxonomic group and b) percent composition.

Cumulative species richness and declining richness over time

Cumulative species richness mirrored annual pulses of debris arrivals in spring (Figure 7-5). Overall cumulative diversity had not yet reached an asymptote at time of publication, suggesting that total arriving diversity of macroinvertebrates was likely considerably larger. Analysis of species richness focused on "Category 1" vessels (Figure 7-6) demonstrated declining diversity since 2014, as might be expected from longer and longer sea voyages by coastal species.

Twelve invertebrate species occurred on 35 or more objects (Table 7-3). More than 40% 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*, also was very common, occurring on one-third of all objects, followed by the large Asian rose barnacle *Megabalanus rosa*. Two thirds of the most common species were bivalves, bryozoans, and barnacles (Table 7-3). All common species arrived alive in Pacific North American waters, with at least seven species surviving the warmer, oligotrophic voyage to the Hawaiian Islands.

No fewer than 109 species -- or 40% of the total macro-invertebrate and fish diversity - were found only once (Table 7-4). Eight objects with more than three unique species aboard accounted for half of these species alone (Table 7-4), or approximately 20% of the biota. An additional 45 objects, each with 1 or 2 unique species, accounted for the remaining presence of "one-off" occurrences (Appendix 7-4).

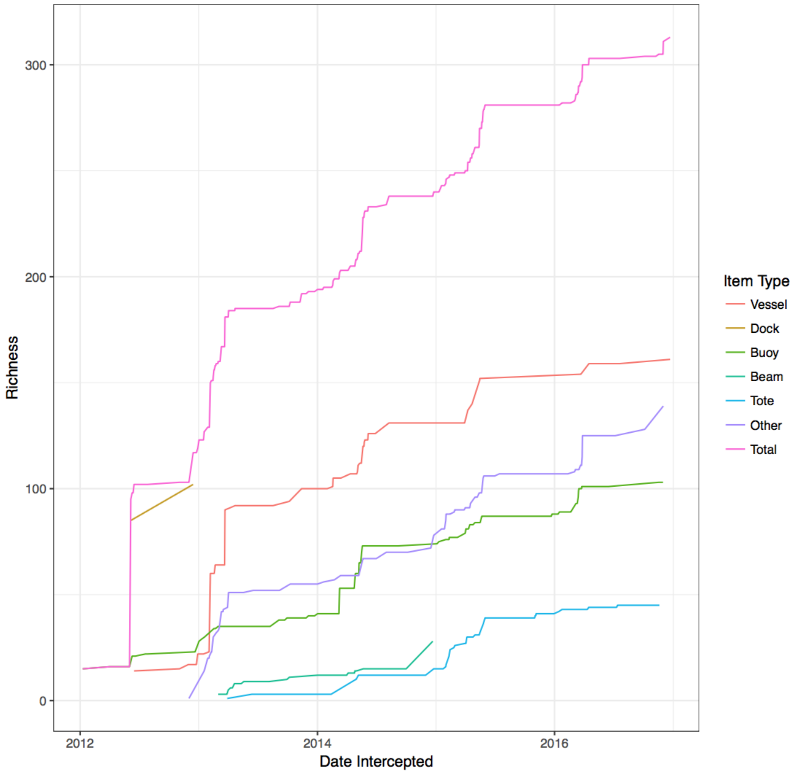


Figure 7-5. JTMD cumulative species richness over time.

Table 7-3. The 12 most frequent marine invertebrates found on JTMD (2012-2016), based on those species occurring on more than 35 objects.

Taxon	Species	Common name	# objects	% (n=653)	Landing Sites	
					NA	Hawaii
Bivalvia	Mytilus galloprovincialis	Mediterranean mussel	281	43.0	x	x
Bryozoa	Scruparia ambigua	Bryozoan	221	33.8	x	x
Cirripedia	Megabalanus rosa	Rose barnacle	112	17.0	x	x
Bryozoa	Aetea spp. (2 species)	Bryozoan	81	12.4	x	x
Bivalvia	Crassostrea gigas	Pacific oyster	76	11.6	x	x (dead only)
Annelida	Hydroides ezoensis	Tube worm	53	8 .1	x	x
Amphipoda	Jassa marmorata	Amphipod	44	6.7	x	--
Bryozoa	Bugula sp.	Bryozoan	39	5.9	x	--
Isopoda	Ianiropsis serricaudis	Isopod	39	5.9	x	x
Bivalvia	Hiatella orientalis	Clam	39	5.9	x	x (dead only)
Cirripedia	Balanus trigonus	Barnacle	37	5.7	x	x

Table 7-4. Unique species occurrences on JTMD.

	A	B	D			
BF-	**Total invertebrate and fish diversity (excluding microbiota)**	**No. of unique species**	**Percentage of total macro-invertebrate and fish biodiversity (n = 287)**	**Object**	**Landing Location**	**Date**
Objects with 3 or more unique species:						
1	84	21		Misawa Dock (M1)	OR	June 2012
8	40	3		Misawa Dock (M3)	WA	Dec. 2012
23	49	10		Vessel	OR	February '13
32	17	3		Dock piece	HI	March 2013
40	47	5		Vessel	WA	March 2013
356	26	4		Vessel	OR	April 2015
402	40	7		Vessel	WA	May 2015
667	22	3		Ropes/ Buoys	HI	December 2016
Subtotal (8 objects)	**--**	**56**	**21 %**			
Appendix 7-**4** (45 additional items with 1 or 2 unique species)		53		Various	See A-4	2012-2016
Total		**109**	**40.8 %**			

Temporal and spatial patterns of biodiversity

For purposes of understanding spatial and temporal patterns of diversity on JTMD, and while contributing importantly to the overall diversity, both the protistan guilds (of about 20 species; Table 7-2) and the microbiota guilds (of about 30 species; Table 7-2) are not further considered, as their sampling was uneven across objects and regions during the course of the work. Thus, the effective denominator for analyzing overall diversity is 267 species (Table 7-2).

As expected, not all species survived the voyage (Appendix 7-5) but the number that arrived as dead-only taxa was surprisingly low, given the length and time duration of the voyages across what is usually considered to be a largely hostile environment for neritic (coastal) species. Approximately 40 species, largely bivalve mollusks and bryozoans, arrived dead. Six of the bivalve species with subtropical affinities (Appendix 7-5), including *Spondylus cruentus, Scaeochlamys squamata, Laevichlamys irregularis, Pascahinnites coruscans, Limaria hakodatensis*, and *Chama* sp. A, arrived dead in the cold waters of Oregon and Washington. Altogether, a little less than one-third of the species that arrived dead were warm-affinity taxa (see section below and Appendix 7-6).

Given that only a relatively small fraction of the arriving JTMD field was sampled biologically, it is probable that the species found dead-only in the current study may have arrived alive at other times and locations on objects not accessed and sampled. Thus, for example, tropical oysters, scallops, and chamids that arrived in the Pacific Northwest may have also arrived on undetected or unsampled debris in the Hawaiian Islands. Further complicating our full assessment of mortality patterns was that it was not always possible to determine whether a given species died after arrival on a particular shore, but before sampling was possible. Therefore, post-landing mortality may have artificially inflated the number of species appearing not to survive the voyages.

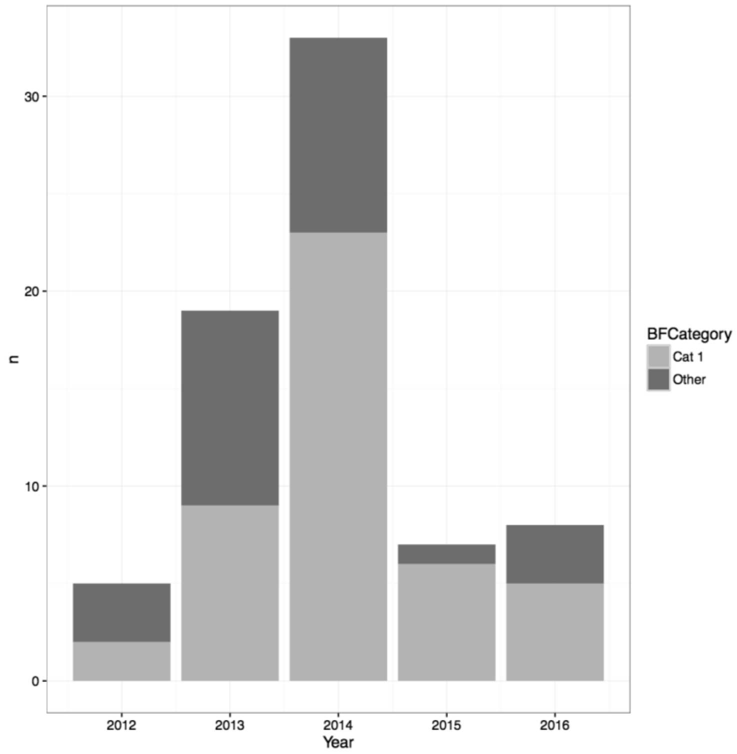


Figure 7-6. Richness decreasing on "Cat 1" vessels (those that were sampled in such a way as to likely have captured the majority of the diversity of species on those objects) over time, and other vessels.

Individual species survivorship

Also not surprising, and in concordance with the debris field having a known start date (March 11, 2011) and a presumed longer-term end date some years from now, was that the overall ratio of living to dead arrivals has shifted over time. That is, given the generally presumed lower trophic resources, higher salinities, increased UV-B exposure, and other rigors of existence on the high seas, living species on oceanic debris tuned to survival in shallow-water, near-shore coastal environments should become increasingly rare as the years go by. How long certain species will live, grow, and survive while at sea for multiple years is largely unknown. Mortality appears, however, to be increasing, with generally fewer species arrivals over time, and with an increasing number of dead individuals. As an example, while living individuals do persist in small numbers, dead individuals now surpass living individuals in species such as the barnacles *Megabalanus rosa* and *Semibalanus cariosus* (Figure 7-7). A detailed example of the increase in mortality for the rose barnacle *Megabalanus* is shown in Figure 7-8, with a higher proportion arriving dead than alive arriving by late 2015. A singular exception was the remarkable survival of the mussel *Mytilus galloprovincialis*, for which the number of living individuals always exceeded the number of dead mussels over time (Figure 7-9). Little is understood of the oceanic physiology of this bivalve to understand its ability to sustain for multiple years on the high seas (but see Chapter 11).

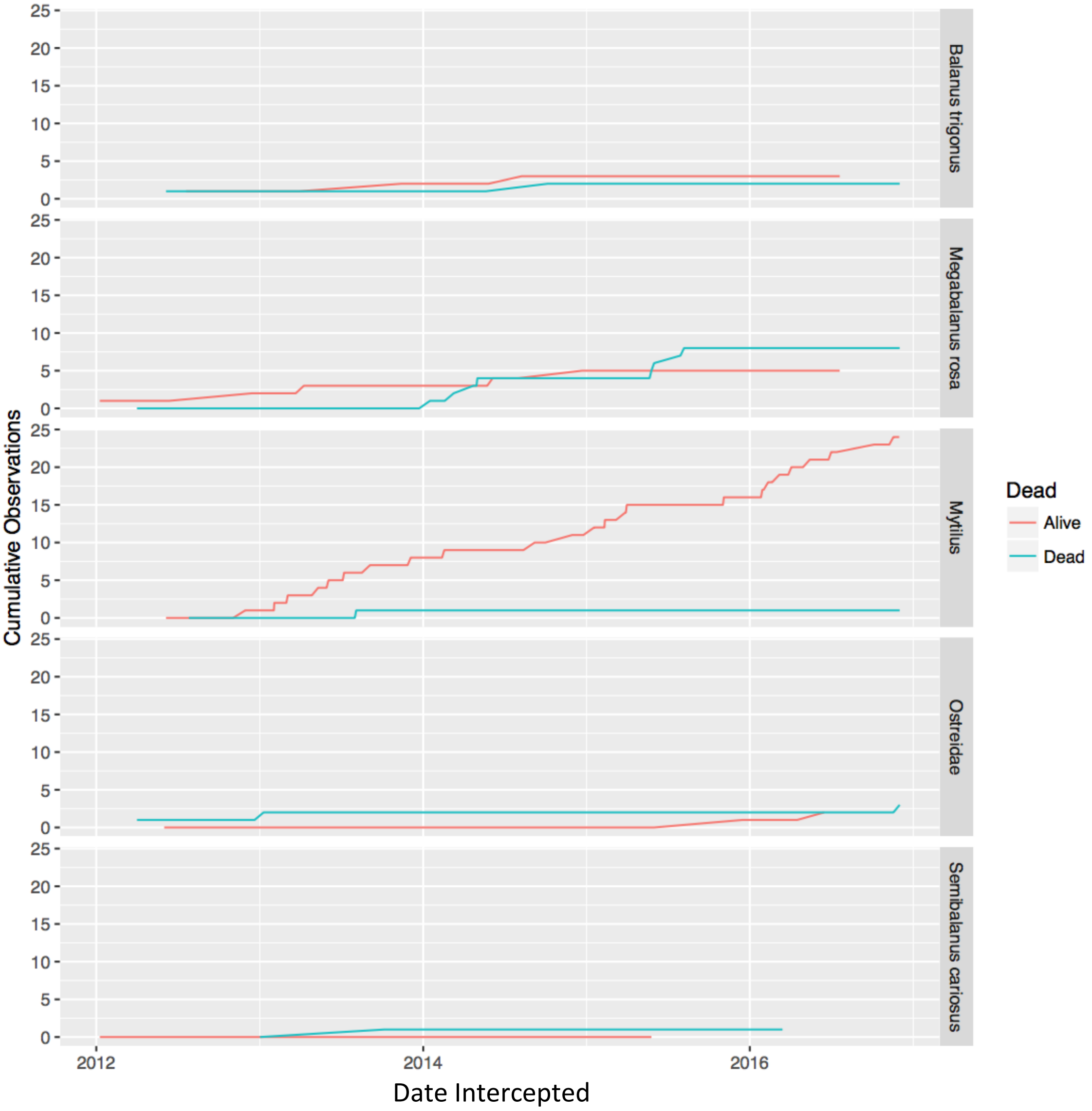


Figure 7-7. Survival status of JTMD species found on debris over time.

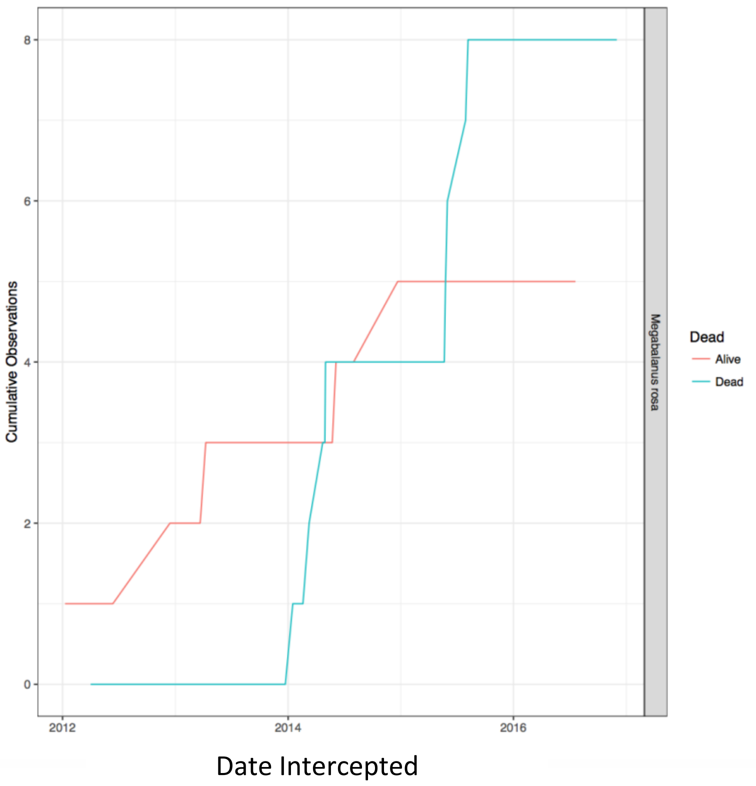


Figure 7-8. Survival status of the barnacle *Megabalanus rosa* found on debris over time.

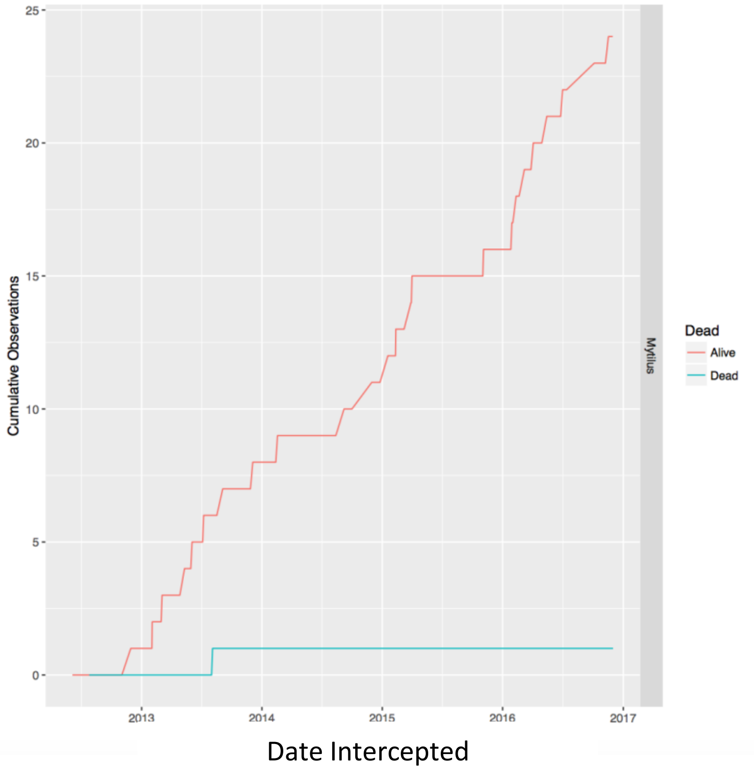


Figure 7-9. The status of JTMD mussels, *Mytilus galloprovincialis*, found on debris over time.

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 nearly 40 adult species acquired by the debris from south of the Tohoku coast, during ocean rafting (Appendix 7-6). In addition, 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 being 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 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 3 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 (10 species), and 2014 and later (24 species). These results suggest that the debris continued to take a wider and longer circuitous path through lower latitudes of the North Pacific.

The spring 2016 sea anemone pulse


Anthopleura asiatica

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A remarkable JTMD landing event occurred in a 47-day episode between March 3 and April 18, 2016 when a pulse of sea anemones arrived with JTMD (Cnidaria: Anthozoa: Actinaria). These species originate 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 1 species not seen since 2014 (Figure 7-10). These species consisted of the Japanese warm-water anemone *Anthopleura asiatica* and the cool-to-warm species *Diadumene lineata* and *Metridium dianthus* (the latter last arrived two years earlier). Thirteen objects were intercepted in this period, with combinations of 1, 2, or 3 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 a nearly 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, and in Phase III, anemone-bearing debris arrived between April 10 and 18, in an even narrower landing zone of about 200 km (Figure 7-10). Observation gaps prevented further fine-grained analysis of this curious pattern, there was a largely unsurveyed area from central California to southern Oregon, and, similarly, the northern coast of Washington and north was largely unsurveyed as well.

The striking southern signature of these landings, in addition to the warm water *Anthopleura asiatica* (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 4 arrivals inFigure 7-10**,** and on an additional 8 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 2 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* and the tropical Indo-West Pacific crab *Sphaerozius nitidus*, the latter represented by a male-female pair.

After April 18, all landings of *Anthopleura asiatica* 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 (compare BF numbers in Figure 7-10 to Appendix 7-1) 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.

JTMD continues to arrive in 2017

Remarkably, JTMD with living Japanese species from the Tohoku coast continues to arrive in North America and the Hawaiian Islands as we approach the close of Year 6 of the JTMD phenomenon (Table 7). 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 recently detected arriving alive include (not surprisingly, now) 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 rope, buoys, and cultured oyster shells, likely derived from the oyster farms of the Tohoku coast, landing in December 2016 at Kapa'a, Kauai, Hawaiian Islands. Debris observers on Kauai with several decades experience reported that nothing similar had landed in more than 25 years of observations.

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 asiatica* (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 asiatica
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 7-10. A 47-day spring 2016 JTMD debris and sea anemone landing event on the Pacific coast of North America.

Table 7-5. Examples of marine life arriving alive on JTMD in November and December 2016.

JTMD-BF	Object	Location	Date	Living Japanese species
661	Black buoy	HI: Hawai'i Island: offshore South Kona, south of Honokohau Harbor	2016 17 November	Mytilus galloprovincialis Aetea truncata Ianiropsis serricaudis Ianiropsis derjugini
662	Kamilo Point blue crate	HI: Hawai'i Island: Kamilo Point	2016 19 November	Mytilus galloprovincialis
663	Blue tote fragment	WA: Long Beach Peninsula	2016 8 November	Mytilus galloprovincialis
664	Long Beach turquoise buoy	WA: Long Beach Peninsula	2016 30 November	Mytilus galloprovincialis
667	Rope and buoy mass from Japanese oyster farm	HI: Kauai: Kapa'a	2016 7 December	Dendrostrea folium Aglaophenia sp. Trypanosyllis zebra Actinaria species A Scruparia ambigua Aetea sp. Catenicella elegans Exochella tricuspis Crisia sp. Entalophora sp.
675	Vessel (5.5m) from Miyagi Prefecture (MG3-38403)	HI: Oahu: Waimanalo	2016 22 December	Actinaria species B Trachypleustes sp. Ampithoe sp.

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 past 3 years through support by the Ministry of 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 perhaps 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 and macroalgal taxa detected on JTMD an underestimate — since many items went undetected and the biota was vastly under sampled 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 hyroid *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 known example is *Haplospordium nelsoni*, which occurs in the native Japanese oyster *Crassostrea gigas* and was introduced to the eastern United States, causing widespread mortality (Burreson et al. 2000, Burreson & 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. However, there is currently no evidence that these species have colonized North America successfully (see Chapter 10).

What makes JTMD different?

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," and (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"? Historic rafting largely consisted of biodegradable materials such trees, tree branches, and root masses. We know little 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, while not impossible, suggests that such events are likely rare. The deterioration and decomposition of post-and-beam wood in about a 2-year period, as observed in this study, suggests 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, suggests 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? We note that JTMD differs from the modern transport of marine life in both ship fouling communities and in ballast water by (1) JTMD having a much slower at-sea transit speed (1-2 knots) *versus* typical commercial vessel speeds of 20 or more knots, thus potentially effecting and impacting the development, adhesion, and retention of fouling communities; (2) JTMD has delivered extensive communities of adult organisms, as compared to planktonic stages of benthic and fouling species in ballast water, (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, as compared to biofouled vessels residing in port for only hours or days. In further future work, we are comparing the biodiversity of JTMD to the biodiversity known from other known vectors, such as the historical transport of Pacific oysters from Japan to North America and Hawaii, historic ship fouling, and modern ship fouling and ballast water communities. A risk assessment of the JTMD vector is presented in Chapter 16.

References

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Appendices

Appendix 7-1. Japanese Tsunami Marine Debris. JTMD-BF Register by object

Appendix 7-2. Scientists Contributing to JTMD Taxonomic Effort

Appendix 7-3. JTMD-Biodiversity: Master species list as of January 30, 2017

Appendix 7-4. Unique species occurrences

Appendix 7-5. Species arriving dead-only on JTMD

Appendix 7-6. Species on JTMD from southern waters

Appendix 7-1. Japanese Tsunami Marine Debris. JTMD-BF Register by object

Criteria for JTMD recognition detailed in text

As of 1.31.17, 677 items are shown, but 24 items have been de-registered. N = 653 as of Report Date.

Register Number Japanese Tsunami Marine Debris (JTMD) Biofouling (BF)	Type of Item	Name JWC John W. Chapman NT Nancy Treneman HI State of Hawaii WDFW Wash Dept Fish Wildlife	State/ Territory/ Province	Location	Date of Collection (not in chronological order)	Category 1
JTMD-BF-1	dock	Misawa 1 (M1)	OR	Agate Beach	2012 June 5	Yes
JTMD-BF-2	vessel	Ilwaco boat / Name of boat: 壮 洋 (Sou-you; "Vast Ocean" or “Prosperous Ocean”	WA	Ilwaco	2012 June 15	Yes
JTMD-BF-3	float	Thompson float	OR	off Lincoln City	2012 June 9	Yes
JTMD-BF-4	float	OR offshore float	OR	off Alsea Bay	2012 June	
JTMD-BF-5	float	Bodega float	CA	Bodega Bay	2012 June 19	
JTMD-BF-6	vessel	Kahana Bay boat; Name of boat: 美和丸 (Miwa-maru; "Beautiful Harmony")	HI	Oahu	2012 November 29	Yes
JTMD-BF-7	float	Oceanus buoy	OR	at sea, nearshore central OR	2012 June 12	
JTMD-BF-8	dock	Misawa 3 (M3)	WA	Olympic National Park	2012 December 18	Yes
JTMD-BF-9	float	Mosquito Creek float1 三信加工： Sanshin Process (a name of a rubber/ plastic products company)	WA	Olympic National Park	2012 December 20	
JTMD-BF-10	float	Mosquito Creek float2	WA	Olympic National Park	2012 December 20	
JTMD-BF-11	vessel	Punaluu boat / Name of boat: 正利丸(Shouri-maru; "Right Profit")	HI	Oahu: Punaluu	2012 December 24	

JTMD-BF-12	vessel	Damon Point boat	WA	Grays Harbor	2012 December 28	
JTMD-BF-13	float	Goodman Creek float	WA	Olympic National Park	2012 July 20	
JTMD-BF-14	float	Fort Bragg float	CA	north of Ft. Bragg	2012 April 1	
JTMD-BF-15	float	Fort Ross float	CA	off Ft. Ross	2012 July 26	
JTMD-BF-16	pallet	Midway pallet	Midway	Eastern Island	2012 November 2	
JTMD-BF-17	float	Hanauma Bay float	HI	Oahu	2013 January 9	Yes
JTMD-BF-18	float	Astoria float	OR	Clatsop Beach	2013 January 9/10	Yes
JTMD-BF-19	vessel	Honokohau boat	HI	Hawaii (Big Island)	2013 January 15	
JTMD-BF-20	cylinder	Mokuleia red metal cylinder (6'wide)	HI	Oahu	2013 January 17	Yes
JTMD-BF-21	buoy	Nohili Point buoy (Barking Sands) 国土交通省小名浜港港湾事務所 (Ministry of Land, Infrastructure, Transport and Tourism, Onahama Harbor Office)	HI	Kauai	2013 January 18	
JTMD-BF-22	refrigerator	Ocean City Refrigerator	WA	Ocean City State Park	2013 February 2	
JTMD-BF-23	vessel	Gleneden boat (AKA Salishan boat)	OR	Gleneden Beach	2013 February 5	Yes
JTMD-BF-24	pallet	South Beach pallet (むらせグループ: Murase Group, a rice corporation)	OR	South Beach	2013 February 8	Yes
JTMD-BF-25	vessel	Kahuku skiff Name of boat: ひさ丸 Hisa-maru (The life jacket has a text that says 長清水, which is a name of a town in Miyagi prefecture)	HI	Oahu	2013 February 13	
JTMD-BF-27	dock	Makapuu dock	HI	Oahu	2013 February 14	Yes
JTMD-BF-28	vessel	Horsfall skiff Name of boat:	OR	Horsfall Beach [not Horsefall]	2013 February 20	Yes

		The "Third" Thriving (第三隆昌丸 [Dai-San-Ryu-Sho-Maru])				
JTMD-BF-29	vessel	Clatsop Beach boat / Name of boat: [○] 龍丸 (fragmentary, missing first word(s): (something- Ryu-Maru; "Dragon")	OR	Clatsop Beach	2013 February 27	
JTMD-BF-30	vessel	Roads End fragment	OR	Lincoln City	2013 February 28	
JTMD-BF-31	rope	Laie rope floats	HI	Oahu: Laie	2013 March 4	
JTMD-BF-32	dock (concrete/foam piece)	Ahihi Kinau dock	HI	Maui	2013 March 11	Yes
JTMD-BF-33	buoy	Kahalu'u buoy	HI	Oahu	2013 March 7	
JTMD-BF-34	ropes and buoys	Kauai ropes/buoys	HI	Kauai: Lepeuli Beach fide Bishop Museum work sheet	2013 February 20	
JTMD-BF-35	buoy	Kahuku buoy	HI	Oahu	2013 February 21	
JTMD-BF-36	vessel	Muriel Ponsler skiff Name of boat:第二合栄丸(Dai-ni-gou-ei-maru: The Second Aggregated Prosper)	OR	Florence	2013 March 14	
JTMD-BF-37	box	Olympic styrofoam box Japanese: "Flammable, keep away from fire"	WA	Olympic National Park	2013 March 17	Yes
JTMD-BF-38	buoy	Lighthouse buoy	OR	Cape Arago	2013 March 17	
JTMD-BF-39	vessel	Cannon Beach skiff Name of boat: なぎさ丸 (Nagisa-maru; "Beach")	OR	Cannon Beach	2013 March 21	Yes
JTMD-BF-40	vessel	Long Beach skiff Name of boat: 斎勝丸 (Sai-shō-maru, The Dignified Victory)	WA	Long Beach	2013 March 22	Yes
JTMD-BF-41	buoy	Kanapou buoy	HI	Kahoolawe	2013 March 13	
JTMD-BF-42	log	Salishan log (wood)	OR	Lincoln City	2013 April 9	Yes

JTMD-BF-43	vessel	Westwind Camp boat	OR	North of Lincoln City (Westwind Camp)	2013 April 7/8	Yes
JTMD-BF-44	post-and-beam wood	Ucluelet P&B-1	BC	Ucluelet	2013 March 28	
JTMD-BF-45	post-and-beam wood	Ucluelet P&B-2	BC	Ucluelet	2013 April 8	
JTMD-BF-46	post-and-beam wood	Ucluelet P&B-3	BC	Ucluelet	2013 April 8	
JTMD-BF-47	post-and-beam wood	Nye Beach P&B-1	OR	Nye Beach, Newport	2013 April 14	
JTMD-BF-48	post-and-beam wood	Nye Beach P&B-2	OR	Nye Beach, Newport	2013 April 14	
JTMD-BF-49	bin (fish container)	Lanikai Beach bin (plastic fish container)	HI	Oahu	2013 March 29	
JTMD-BF-50	vessel	Coos Bay skiff	OR	Coos Bay, North Spit	2013 April 22	Yes
JTMD-BF-51	pallet	North Spit pallet 1	OR	Coos Bay, North Spit	2013 April 25	
JTMD-BF-52	pallet	North Spit pallet 2	OR	Coos Bay, North Spit	2013 April 25	
JTMD-BF-53	post-and-beam wood	Ucluelet P&B-4	BC	Ucluelet	2013 April	
JTMD-BF-54	float	Kamilo float	HI	Big Island: Kamilo Beach	2013 April 8	
JTMD-BF-55	post-and-beam wood	Moolack P&B-1	OR	Lincoln Co.: Moolack Beach	2013 May 11	
JTMD-BF-56	tree	South Beach tree	OR	Lincoln Co.: South Beach	2013 April 17	
JTMD-BF-57	post-and-beam wood	South Beach P&B-1	OR	Lincoln Co.: South Beach	2013 May 8	
JTMD-BF-58	fiberglass boat	Clatsop boat fragment	OR	Clatsop Beach	2013 May 30	Yes
JTMD-BF-59	post-and-beam wood	Nye Beach P&B-3	OR	Nye Beach, Newport	2013 May 30	
JTMD-BF-60	post-and-beam wood	Tillamook lumber	OR	Tillamook: Bay Ocean Beach	2013 May 19	
JTMD-BF-61	post-and-beam wood	Nye Beach P&B-4 106x9x9 beam	OR	Nye Beach, Newport	2013 May 30	

JTMD-BF-63	post-and-beam wood	Grayland P&B	WA	Grayland Beach North	2013 April 21	
JTMD-BF-64	post-and-beam wood	Yaquina Head P&B	OR	Yaquina Head	2013 June 3	
JTMD-BF-65	post-and-beam wood	Lost Creek P&B-1	OR	Lost Creek	2013 June 9	
JTMD-BF-66	post-and-beam wood	Lost Creek P&B-2	OR	Lost Creek	2013 June 9	
JTMD-BF-67	pallet	North Cove pallet: 森永乳業大和工場: Morinaga Milk Yamato Factory (a pallet from Tokyo)	OR	Cape Arago: North Cove	2013 June 18	Yes
JTMD-BF-68	refrigerator (minifridge)	Kamilo Point minifridge-1	HI	Big Island: Kamilo Point	2013 February	
JTMD-BF-69	refrigerator (minifridge)	Kamilo Point minifridge-2	HI	Big Island: Kamilo Point	2013 March 16	
JTMD-BF-70	TV Set	Kamilo Point TV set	HI	Big Island: Kamilo Point	2013 June 23	
JTMD-BF-71	pallet	Kalaloch pallet	WA	Olympic National Park	2013 June 23	Yes
JTMD-BF-72	I-beam /styrofoam	Punaluu I-beam	HI	Oahu: Punaluu	2013 June 17	
JTMD-BF-73	piling	Whiskey Run piling	OR	Coos County: Whiskey Run Beach	2013 July 8	
JTMD-BF-74	post-and-beam wood	Whiskey Run P&B-1	OR	Coos County: Whiskey Run Beach	2013 July 8	
JTMD-BF-75	vessel	Malaekahana boat Myo-ei maru (妙栄丸) "Remarkable Prosper" (or, “Skillful Prosper”); a text on the boat says イトウマリンサービス(Itoh Marine Service), which is a marine transportation company based in Ofunato city, Iwate	HI	Oahu: Laie: Malaekahana Beach	2013 July 5	
JTMD-BF-76	buoy	Kenai orange buoy	AK	Kenai Fjords National Park	2013 June 24	

JTMD-BF-77	box	WCT blue box 岩手大船渡港　鎌田水産: Iwate Prefecture Ofunato Harbor Kamata Marine Industry (A marine product company cased in Ofunato, Iwate)	BC	Vancouver Is: between Bamfield and Port Renfrew	2013 June 13	
JTMD-BF-78	vessel	Makah boat: "検査済 日本小型船舶検査機構: "Examined by Japan Craft Inspection Organization" and "Maximum two people on board"	WA	Makah Reservation	2013 May 12	
JTMD-BF-79	buoy	Bandon buoy #1	OR	Bandon region	2013 Winter-summer	
JTMD-BF-80	buoy	Bandon buoy #2	OR	Bandon region	2013 Winter-summer	
JTMD-BF-81	pallet	Bandon blue pallet (label in Japanese: "This is made of polythene so please keep fire away ")	OR	Bandon region	2013 Winter-summer	
JTMD-BF-82	maritime/ vessel board	Coos Bay board	OR	"Coos Bay area"	2013 March 30	Yes
JTMD-BF-83	bottle	Turret plastic bottle (52 mm tall)	BC	Vancouver Is.: Turret Is.	2013 May 18	
JTMD-BF-84	buoy	Campbell 3'-foam buoy	HI	Oahu: James Campbell NWR	2013 week of July 8	
JTMD-BF-85	buoy with rope	Campbell 5'-foam buoy with 1.5m woven rope	HI	Oahu: James Campbell NWR	2013 week of July 8	
JTMD-BF-86	post-and-beam wood	Sebastian P&B (= NT4+13+16)	OR	North of Cape Sebastian: Kissing Rock (KR)	2013 August 4	
JTMD-BF-87	vessel	Kawela boat, 20-25'	HI	Oahu: Kawela	2013 August 14	
JTMD-BF-88	vessel	Turtle Bay boat マーシ (too incomplete)	HI	Oahu: Turtle Bay Resort	2013 August 17	
JTMD-BF-89	post-and-beam wood	Bay Ocean P&B	OR	Tillamook Co.: Bay Ocean Peninsula	2013 July 28	
JTMD-BF-90	buoy	Keauhou buoy	HI	Kona coast: 1 mile off, around Keauhou	2013 September 4	Yes
JTMD-BF-91	buoy	Red Hill buoy	HI	Kona coast: 1 mile offshore, around Red Hill	2013 September 5	
JTMD-BF-92	buoy	Kamilo white styrofoam buoy 3 ft	HI	Big Island: Kamilo	2013 July 12	

JTMD-BF-93	buoy,	Yamani white styrofoam buoy 3 ft	AK	Sitka area: SSSC/ Cherokee, Yamani area	2013 August 8	
JTMD-BF-94	vessel fragment	Ucluelet boat	BC	Vancouver Island: Ucluelet area	2013 winter-spring	
JTMD-BF-95	post-and-beam wood	Ucluelet P&B-5	BC	Vancouver Island: Ucluelet area	2013 March-April	
JTMD-BF-96	buoy	Au'au Buoy #1, orange "南フロ" (too incomplete)	HI	Maui: Au'au channel between Maui and Lana'i	2013 September 22	
JTMD-BF-97	post-and-beam wood	Long Beach Peninsula P&B	WA	Long Beach Peninsula, N46.43.127, W124.06.12	2013 April 20	
JTMD-BF-98	post-and-beam wood	South Beach P&B-2	OR	South Beach	2013 April 17	
JTMD-BF-99	post-and-beam wood	Moolack Beach P&B#1	OR	Moolack Beach	2013 May 6	
JTMD-BF-100	post-and-beam wood	Moolack Beach P&B#2	OR	Moolack Beach	2013 May 6	
JTMD-BF-101	post-and-beam wood	Moolack Beach P&B#3	OR	Moolack Beach	2013 May 6	
JTMD-BF-102	post-and-beam wood	Fogarty Creek P&B	OR	Fogarty Creek Beach	2013 May 8	
JTMD-BF-103	buoy	Bandon styrofoam buoy #1, large white	OR	Bandon region	late 2012 to early 2013	
JTMD-BF-104	buoy	Bandon styrofoam buoy #2, large white	OR	Bandon region	late 2012 to early 2013	
JTMD-BF-105	buoy	Bandon styrofoam buoy #3, large white	OR	Bandon region	late 2012 to early 2013	
JTMD-BF-106	buoy	Cape Blanco styrofoam buoy, large white	OR	Cape Blanco	2013 July 11	
JTMD-BF-107	post-and-beam wood	Whiskey Run beach P&B	OR	Whiskey Run Beach	2013 July 8	
JTMD-BF-108	post-and-beam wood	Lighthouse Beach P&B #1	OR	Cape Arago: Lighthouse Beach	2013 July 11	
JTMD-BF-109	post-and-beam wood	Lighthouse Beach P&B #2	OR	Cape Arago: Lighthouse Beach	2013 July 13	
JTMD-BF-110	post-and-beam wood	Ucluelet #7	BC	Ucluelet	2013 Spring	
JTMD-BF-111	post-and-beam wood	Ucluelet burned wood	BC	Ucluelet	2013 Spring	

JTMD-BF-112	post-and-beam wood	Sand Point P&B	WA	Sand Point South, Olympic National Seashore	2013 April 20	
JTMD-BF-113	post-and-beam wood	Cape Alava P&B	WA	Olympic National Park: near Cape Alava	2013 September 20-21	
JTMD-BF-114	post-and-beam wood	P&B NT1	OR	Rocky Point south of Port Orford	2013 July 19	
JTMD-BF-115	post-and-beam wood	P&B NT2	OR	Rocky Point south of Port Orford	2013 July 19	
JTMD-BF-116	post-and-beam wood	P&B NT3 [Note: NT4 is BF-86]	OR	Crook Point, south of Gold Beach	2013 August 3	
JTMD-BF-117	post-and-beam wood	P&B NT5	OR	Lone Ranch State Park, Brookings	2013 August 5	
JTMD-BF-118	post-and-beam wood	P&B NT6	OR	South Cove, Cape Arago	2013 August	
JTMD-BF-119	post-and-beam wood	P&B NT7	OR	Pistol River, south of Gold Beach	2013 September 26	
JTMD-BF-120	post-and-beam wood	P&B NT8	OR	North Cove, Cape Arago	2013 October 6	
JTMD-BF-121	post-and-beam wood	P&B NT9	OR	North Cove, Cape Arago	2013 October 6	
JTMD-BF-122	post-and-beam wood	P&B NT10	OR	North Cove, Cape Arago	2013 October 6	
JTMD-BF-123	post-and-beam wood	P&B NT11	OR	North Cove, Cape Arago	2013 October 6	
JTMD-BF-124	post-and-beam wood	P&B NT12	OR	Crook Point, south of Gold Beach	2013 November 17	
JTMD-BF-125	post-and-beam wood	P&B NT14	OR	Lost Creek, south of Newport	2014 January 17	
JTMD-BF-126	post-and-beam wood	P&B NT15	OR	Agate Beach, Newport	2014 February 19	
JTMD-BF-127	post-and-beam wood	P&B NT17	OR	Crook Point, south of Gold Beach	2014 February 27	
JTMD-BF-128	post-and-beam wood	P&B NT18	OR	Bandon	2014 March 2	
JTMD-BF-129	vessel	Long Beach BC skiff o月 日 丸 (o moon sun)	BC	Long Beach, outer (west) coast of Vancouver Island	2013 October 6	Yes
JTMD-BF-130	dock piece	Clatsop dock block	OR	Clatsop Beach: one km from Del Rey beach access	2013 October 9	Yes

JTMD-BF-131	vessel	Tokeland-Grayland skiff 八漁福丸 (Eight- Fishing- Fortune; the complete text is probably: 第八漁福丸)	WA	between Grayland Beach State Park and Tokeland (N 47.7271 W -124.0510).	2013 November 13	Yes
JTMD-BF-132	buoy	Au'au buoy #2, orange o南ブロ(o-South-??)	HI	Maui: Au'au channel between Maui and Lana'i	2013 November 27	
JTMD-BF-133	buoy	Au'au buoy #3	HI	Maui: Au'au channel between Maui and Lana'i	2013 December 4	
JTMD-BF-134	vessel	Twin Harbors boat, 22 feet 第18栄福丸 (The Eighteenth Prosperous-Fortune)	WA	Twin Harbors State Park, Westport N 46.86506 x W124.11851	2014 January 16	Yes
JTMD-BF-135	vessel piece	Yachats skiff fragment, 13'5" x 21", fiberglass S230	OR	just north of Yachats	2014 February 17 (18)	Yes
JTMD-BF-136	lid	South Beach pink lid	OR	South Beach, 4 mile walk (Lost Creek)	2014 February 22	
JTMD-BF-137	post-and-beam wood	South Beach P&B #2 of this day South Beach P&B-3 /See 157 for #1	OR	South Beach, 4 mile walk	2014 February 22	
JTMD-BF-138	boat fragment	Kamilo boat fragment, large	HI	Kamilo Beach	2014 Late January; retrieved February 28	
JTMD-BF-139	vessel	Pearl Harbor – Hickam skiff (15')	HI	On reefs at Pearl Harbor – Hickam field	2014 February 18	Yes
JTMD-BF-140	cooler	Leadbetter plastic cooler (formerly “Long Beach cooler”)	WA	Leadbetter Point	2012 December	
JTMD-BF-141	lid	Long Beach lid, plastic	WA	Long Beach Peninsula	2013 March	
JTMD-BF-142	buoy	Hanauma Bay Buoy #2, black	HI	Hanauma Bay	2013 May 29	
JTMD-BF-143	pallet	Kailua Beach pallet, 4 ft square	HI	Kailua Beach	2013 September 6	
JTMD-BF-144	buoy	Waipake-Lepeuli buoy	HI	Waipake and Lepeuli	2013 29 September	
JTMD-BF-145	buoys (2)	Moanalua Bay buoy	HI	Kauai: Moanalua Bay	2013 October 12	
JTMD-BF-146	post-and-beam wood	Waipake P&B	HI	Kauai: Waipake	2013 October	
JTMD-BF-147	marine buoy, lighted	Hanamaulu buoy, marine, lighted, 10'	HI	Kauai: Hanamaulu Beach Park	2013 November 8	

JTMD-BF-148	vessel fragment	Waihee skiff (piece); イワなわ (incomplete or an abbreviation; possibly from Iwate	HI	Maui: Kalepa Gulch: Waihee	2014 February	
JTMD-BF-149	fishing buoy	Waipake buoy	HI	Kauai: Waipake Beach, NE Kauai	2013 April 27	
JTMD-BF-150	post-and-beam wood	P&B NT19	OR	North Cove, Cape Arago	2014 March	
JTMD-BF-151	post-and-beam wood	P&B NT20	OR	North Cove, Cape Arago	2014 March	
JTMD-BF-152	vessel	Midway skiff: 伝宝丸 (The Link to the Treasure)	HI	Midway: Eastern Island	2012 November 2	
JTMD-BF-153	buoy	Midway buoy #1	HI	Midway	2013 February 16	
JTMD-BF-154	buoy	Midway styrofoam buoy	HI	Midway	2012-2013	Yes
JTMD-BF-155	oyster buoy	Midway oyster buoy	HI	Midway: Eastern Island	2014 February 14	
JTMD-BF-156	buoy	Midway buoy #2	HI	Midway: N28.20830 x W 177.34088	2012-2013	
JTMD-BF-157	post-and-beam wood	South Beach P&B #1 of this day See 137 for #2 South Beach P&B-4 = NT 21	OR	South Beach, 4 mile walk	2014 February 22	
JTMD-BF-158	fiberglass (fish?) box	Malaekahana box	HI	Oahu: Malaekahan Beach Park	2014 February 12	
JTMD-BF-159	post-and-beam wood	South Cove P&B	OR	Cape Arago: South Cove	2013 June 16	
JTMD-BF-160	tree	Cape Meares tree NT30	OR	Tillamook Bay outer coast beach, north of Cape Meares (Tillamook Bay spit)	2014 April 26	Yes
JTMD-BF-161	post-and-beam wood	Newport N Jetty P&B #1 = NT 22	OR	Newport: North Jetty	2014 April 3	
JTMD-BF-162	post-and-beam wood	Newport N Jetty P&B #2 = NT 23	OR	Newport: North Jetty	2014 April 5	
JTMD-BF-163	post-and-beam wood	Otter Rock P&B #1 = NT 24	OR	Otter Rock	2014 April 5	
JTMD-BF-164	post-and-beam wood	Otter Rock P&B #2 = NT 25	OR	Otter Rock	2014 April 5	
JTMD-BF-165	post-and-beam wood	Woodruff P&B = NT 26	OR	Woodruff Creek	2013 May	

JTMD-BF-166	post-and-beam wood	Newport N Jetty P&B #3 = NT 27	OR	Newport: North Jetty	2014 April 3	
JTMD-BF-167	post-and-beam wood	Crook Point P&B = NT 28	OR	Crook Point, south side	2014 April 16	
JTMD-BF-168	buoy	Long Beach float	WA	Long Beach	2014 March 10	Yes
JTMD-BF-169	post-and-beam wood	Lighthouse Beach P&B#3	OR	Lighthouse Beach	2013 December	
JTMD-BF-170	vessel	Showa Skiff, Long Beach	WA	Long Beach	2014 April 23	Yes
JTMD-BF-171	post-and-beam wood	Tillamook P&B / NT29	OR	Tillamook: South Jetty Beach	2014 April 25	
JTMD-BF-172	buoy	South Beach orange buoy	OR	Lost Creek, South Beach, 118th St.	2014 April 27	Yes
JTMD-BF-173	buoy	South Beach black buoy	OR	Lost Creek, South Beach, 118th St.	2014 April 27	Yes
JTMD-BF-174	post-and-beam wood	Yaquina Bay P&B-1	OR	Yaquina Bay, beach at Hatfield Station	2014 April 26	
JTMD-BF-175	post-and-beam wood	South Beach P&B-4 S-300	OR	Lost Creek State Park, South Beach, 118th St.	2014 April 29	
JTMD-BF-176	post-and-beam wood	South Beach P&B-5	OR	Lost Creek, South Beach, 118th St.	2014 April 29	
JTMD-BF-177	vessel	Ocean City State Park (SP) / "Ocean Shores" skiff	WA	Ocean Shores, "off Ocean Lake Way"	2014 April 28	Yes
JTMD-BF-178	post-and-beam wood	Ucluelet P&B-6	BC	Ucluelet area: Salmon and Beach	2014 March 9/10	
JTMD-BF-179	post-and-beam wood	Ucluelet P&B-7	BC	Ucluelet area: Salmon and Beach	2014 March 9/10	
JTMD-BF-180	post-and-beam wood	Ucluelet P&B-8	BC	Ucluelet area: Broken Group Islands	2014 April 8	
JTMD-BF-181	buoy	Long Beach orange buoy Lewis #1	WA	Long Beach	2013 March	
JTMD-BF-182	post-and-beam wood	Long Beach Peninsula P&B #2	WA	Long Beach	2013 March	
JTMD-BF-183	buoy	Long beach buoy Lewis #2	WA	Long Beach	2014 April 24	
JTMD-BF-184	buoy	Long beach buoy Lewis #3	WA	Long Beach	2014 April 24	

JTMD-BF-185	post-and-beam wood	South Beach P&B-6	OR	Lost Creek, South Beach, 118th St.	2014 April 29	
JTMD-BF-186	bin piece	Lost Creek plastic bin, white, piece	OR	Lost Creek, South Beach, 118th St.	2014 April 30	
JTMD-BF-187	buoy	Catherine Island black buoy	AK	Catherine Island, Chatham Strait	2014 April 30	
JTMD-BF-188	vessel	Cape Lookout skiff #1	OR	Cape Lookout Beach	2014 May 2?	Yes
JTMD-BF-189	float	Cape Lookout float #1, blue	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-190	propane tank	Cape Lookout propane tank	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-191	plastic fragment	Cape Lookout plastic fragment	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-192	float	Cape Lookout float #2, white	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-193	float,	Cape Lookout float #3, white oysters	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-194	post-and-beam wood	Cape Lookout post-and-beam #1	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-195	post-and-beam wood	Cape Lookout post-and-beam #2	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-196	vessel	Waldport skiff	OR	Waldport	2014 May 11	Yes
JTMD-BF-197	dock float	Quinault dock float	WA	Quinault Indian Reservation	2014 May 9	Yes
JTMD-BF-198	vessel	Tierra del Mar boat	OR	Sand Lake region	2014 May 12	Yes
JTMD-BF-199	vessel	Umpqua skiff	OR	North of the Umpqua River	2014 May 15	Yes
JTMD-BF-200	float	Manzanita float	OR	Rockaway: Manzanita State Park	2012 April	
JTMD-BF-201	vessel, 25 feet x 70 inches	Brian Booth SP skiff	OR	Just N of Beaver Creek at Brian Booth State Park	2014 May 16	Yes
JTMD-BF-202	vessel	Surfland Skiff	OR	Surfland, about 3 mi south of Newport	2014 May 16	Yes
JTMD-BF-203	buoy	Long beach buoy Lewis #4	WA	Long Beach	2013 April	

JTMD-BF-204	buoy	Kauai buoy	HI	Kauai	2014 March 8	
JTMD-BF-205	vessel	Lepeuli Skiff	HI	Kauai: Larsen's/ Lepeuli Beach	2014 April 12	Yes
JTMD-BF-206	"fuel" (propane?) tank	Waimanalo tank	HI	Oahu: Waimanalo	2014 April 16	
JTMD-BF-207	buoy	Charleston buoy	OR	Coos Bay: Charleston Outer Boat Basin	2014 May 17	Yes
JTMD-BF-208	vessel	Cape Arago skiff	OR	Cape Arago: North Cove	2014 May 19	Yes
JTMD-BF-209	vessel	Haleiwa skiff	HI	Oahu: found offshore and towed into Haleiwa small boat harbor	2014 May 19/20	Yes
JTMD-BF-210	vessel	Carter Lake skiff	OR	Siuslaw region:	2014 May 21	Yes
JTMD-BF-211	vessel	Tahkenitch Lake vessel	OR	Siuslaw region:	2014 May 21	
JTMD-BF-212	concrete dock section	Siuslaw concrete dock section	OR	Siuslaw region:	2014 May 21	Yes
JTMD-BF-213	post-and-beam wood	Cape Blanco P&B#1 (NT33)	OR	Cape Blanco	2014 May 12	
JTMD-BF-214	post-and-beam wood	Cape Blanco P&B#2 (NT32)	OR	Cape Blanco	2014 May 12	
JTMD-BF-215	buoy	Tehakenitch Buoy #1, black	OR	South of Dunes City	2014 May 19	Yes
JTMD-BF-216	buoy	Tehakenitch Buoy #2, black	OR	South of Dunes City	2014 May 19	Yes
JTMD-BF-217	float	Cape Lookout float #4, orange-white	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-218	float	Cape Lookout float #5, orange-white	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-219	float	Cape Lookout float #6, orange	OR	Cape Lookout Beach	2014 May 4	
JTMD-BF-221	vessel	Cape Lookout skiff #2	OR	Cape Lookout Beach	2014 May 25	
JTMD-BF-222	vessel	Ocean Park skiff [Yamaha 21']	WA	Long Beach Peninsula: 0.5mi N of Ocean Park approach	2014 May 23	Yes

JTMD-BF-223	vessel	Bolstad skiff #1 [Yamaha 31’]	WA	Long Beach Peninsula: 0.2mi S of Bolstad and 0.1mi N of Seaview Beach approach	2014 May 24	Yes
JTMD-BF-224	vessel	Bolstad skiff #2 [18’]	WA	Long Beach Peninsula: 0.2mi S of Bolstad and 0.1mi N of Seaview Beach approach	2014 May 24	Yes
JTMD-BF-225	vessel	Neptune skiff	OR	S of Neptune and N of Strawberry Hill	2014 May 27	
JTMD-BF-226	vessel	Grays Harbor skiff	WA	Near Ocean City	2014 May 25	Yes
JTMD-BF-227	vessel	38’ Long Beach skiff (AKA Cranberry Beach skiff)	WA	Long Beach Peninsula	2014 June 5	Yes
JTMD-BF-228	vessel section	Long Beach skiff section (10’)	WA	Long Beach Peninsula	2014 June 5	
JTMD-BF-229	vessel	Quinault skiff	WA	Grays Harbor County	2014 June 6	Yes
JTMD-BF-230	vessel	Kalaloch skiff	WA	Long Beach Peninsula, south of Kalaloch lodge	2014 June 6	
JTMD-BF-231	post-and-beam wood	Crook Point North (=NT34)	OR	South of Pistol River State Park	2014 May 27	
JTMD-BF-232	buoy (“pink float”)	Mile 43 Buoy, red	OR	Mile 43, Port Orford area (Humbug Mountain) (Dale Lee)	2014 May 17	Yes
JTMD-BF-233	skiff bow	Netarts skiff	OR	Netarts Bay (JWC observed it being towed)	2014 June 28	
JTMD-BF-234	propane tank	South Beach propane tank	OR	South Beach	2013 February 9	
JTMD-BF-235	tire	Long Beach tire	WA	Long Beach Peninsula: Oysterville	2013 March 1	
JTMD-BF-236	buoy	Sitka orange buoy	AK	Sitka	2014 May 25	
JTMD-BF-237	buoy	Sitka black buoy #1	AK	Sitka	2014 May 24	Yes
JTMD-BF-239	buoy	Sitka black buoy #2	AK	Sitka	2013	
JTMD-BF-240	vessel	Daly City skiff	CA	Daly City: Mussel Rock Beach (south of San Francisco)	2014 August 9	Yes

JTMD-BF-241	motorcycle helmet	Cape Meares helmet	OR	Cape Meares AKA Bay Ocean	2014 August 19	Yes
JTMD-BF-242	buoy	Maui buoy	HI	Maui	2014 September 7	
JTMD-BF-244	post-and-beam wood	NT 35	BC	Vancouver Island: Ucluelet	2014	
JTMD-BF-245	post-and-beam wood	NT 36	BC	Vancouver Island: Ucluelet	2014	
JTMD-BF-246	post-and-beam wood	NT 37	BC	Vancouver Island: Ucluelet	2014	
JTMD-BF-247	post-and-beam wood	NT 38	OR	Cape Arago: North Cove	2014	
JTMD-BF-248	post-and-beam wood	NT 39	OR	Cape Arago: North Cove	2014	
JTMD-BF-249	buoy	MacKerricher Buoy	CA	MacKerricher State Park, Mendocino Co.	2014 August 13	
JTMD-BF-250	vessel	Dry Lagoon skiff (skiff #25 in spring landing)	CA	Dry Lagoon	2014 June 6	
JTMD-BF-251	buoy	Amphitrite Beach buoy	BC	Amphitrite Beach, Ucluelet	2014 April 28	
JTMD-BF-253	vessel	Kahana skiff	HI	Kahana Bay	2014 April 22	
JTMD-BF-254	tote	Lost Creek blue tote	OR	Between Lost Creek and South Jetty	2014 April 29	
JTMD-BF-255	container	Ocean Shores container	WA	Ocean Shores	2014 May 7	Yes
JTMD-BF-257	concrete floating dock	Sandy's Beach dock = HI56 (row 252)	HI	Between Sandy's Beach and ERMA, Oahu	2014 October 6	
JTMD-BF-258	container box doors (one unit)	Quail Street Doors; ; about 8' x 8.5' (6.5 x 5.5 crowbars)	OR	between Newport and Waldport: Seal Rock: Quail Street	2013 February 23	Yes
JTMD-BF-259	carboy	Bay Ocean carboy, white	OR	Bay Ocean	2013 February	
JTMD-BF-260	wooden dock frame	Retz Creek dock frame, 15'x5'x12"	OR	Retz Creek, just south of Port Orford	2013 March 11	
JTMD-BF-261	post-and-beam wood	NT41	OR	Gold Beach: Kissing Rock	2014 November 18	

JTMD-BF-262	post-and-beam wood	NT42	OR	Bandon	2014 December 12 (spring 2014 landing)	
JTMD-BF-263	post-and-beam wood	NT43	OR	Crooked Creek, Bandon (Devil's Kitchen State Park)	2015 January 2	
JTMD-BF-264	tree	NT44	WA	Oysterville, Long Beach	2014 December 22	Yes
JTMD-BF-265	post-and-beam wood	NT45	OR	Newport: Moolack Beach	check date	
JTMD-BF-266	post-and-beam wood	NT46	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-267	post-and-beam wood (roof beam)	NT47	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-268	post-and-beam wood	NR48	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-269	post-and-beam wood	NT49	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-270	post-and-beam wood	NT50	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-271	post-and-beam wood	NT51	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-272	post-and-beam wood	NT52	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-273	post-and-beam wood (door frame)	NT53	OR	Newport: Moolack Beach	2015 January 9	
JTMD-BF-274	post-and-beam wood	NT54	OR	Newport: South Beach	2015 January 10	
JTMD-BF-275	post-and-beam wood	NT55	OR	Newport: South Beach	2015 January 10	
JTMD-BF-276	post-and-beam wood	NT56	OR	Newport: South Beach	2015 January 10	
JTMD-BF-277	tote 1.67m	Seal Rock tote	OR	Seal Rock	2014 November 30	Yes
JTMD-BF-279	post-and-beam wood	NT57	OR	Lincoln City: Roads End	2015 January 16 (about 2 yrs on beach?)	

JTMD-BF-280	post-and-beam wood	NT58	OR	Lincoln City: Roads End	2015 January 16	
JTMD-BF-281	carbuoy	Oysterville carbuoy (S265), plastic	WA	Oysterville	2014 May 8	
JTMD-BF-282	milled wood	Oysterville wood (S266-7)	WA	Oysterville	2014 May 8	Yes
JTMD-BF-283	buoy	Oysterville black buoy (S268)	WA	Oysterville	2014 May 8	Yes
JTMD-BF-284	float	Long Beach green float	WA	Long Beach	2014 December 23	
JTMD-BF-285 RESTORED	skiff fragment	Long Beach boat fragment	WA	Long Beach	2015 January 4	
JTMD-BF-286	fillet board	Long Beach fillet board	WA	Long Beach	2015 January	
JTMD-BF-287	tote	Long Beach tote	WA	Long Beach	2015 January	
JTMD-BF-288	pallet	Beverly Beach crate (tote)	OR	Beverly Beach, north of Newport	2015 January 20	Yes
JTMD-BF-289	crate	Tillamook South Jetty pink crate	OR	Tillamook South Jetty Beach (north of the Cape)	2015 January 18	
JTMD-BF-290	crate	Tillamook South Jetty red bottle crate	OR	Tillamook South Jetty Beach (north of the Cape)	2015 January 18	
JTMD-BF-291	laundry basket	Tillamook South Jetty laundry basket	OR	Tillamook South Jetty Beach (north of the Cape)	2015 January 18	
JTMD-BF-292	crate (tote)	Tokeland tote	WA	on beach in front of 3167 Kindred Ave., Tokeland	2015 January 20	
JTMD-BF-293	pipe	Seaview pipe/I-beam	WA	Long Beach: Beard's Hollow	2013 January 28	Yes
JTMD-BF-294	post-and-beam wood	Donkey Beach p&b	HI	Kauai: Paliku	2014 September 29	
JTMD-BF-295	sieve lid	Long Beach green sieve lid	WA	Long Beach	2015 January 27	
JTMD-BF-296	post-and-beam wood	NT 59	OR	Bandon: Bullard's Beach	2015 January 31	
JTMD-BF-297	post-and-beam wood	NT 60	OR	Bandon: Bullard's Beach	2015 January 31	
JTMD-BF-298	post-and-beam wood	NT 61	OR	Bandon: Bullard's Beach	2015 January 31	

JTMD-BF-299	basket	Long Beach white bucket	WA	Long Beach	2015 February 11	
JTMD-BF-300	buoy	Toleak Point buoy, black plastic WDFW 517	WA	La Push: Toleak Point	2015 February 10	
JTMD-BF-301	buoy	Strawberry Pt buoy, black plastic WDFW 526	WA	La Push: Strawberry Point	2015 February 11	
JTMD-BF-302	buoy	Strawberry Point, La Push buoy, black plastic WDFW527	WA	La Push: Strawberry Point	2015 February 11	
JTMD-BF-303	buoy	Strawberry Point, La Push buoy, black plastic WDFW529	WA	La Push: Strawberry Point	2015 February 11	
JTMD-BF-304	basket	offshore Newport yellow basket; sample rec'd June 2016	OR	offshore of Newport, at sea	2015 February 12	Yes
JTMD-BF-305	crate	Westwind Camp blue crate	OR	north of Lincoln City	2015 February 13	Yes
JTMD-BF-306	basket	Brookings blue crate (tote, basket)	OR	Brookings	2015 February 10	Yes
JTMD-BF-309	post-and-beam wood	NT63	OR	Cape Arago: South Cove	2015 March 7	
JTMD-BF-310	post-and-beam wood	NT64	OR	Cape Arago: South Cove	2015 March 7	
JTMD-BF-311	post-and-beam wood	NT66	HI	Oahu: Waimanalo Beach	2013(estimated landing date)	
JTMD-BF-312	post-and-beam wood	NT67	HI	Oahu: Waimanalo Beach	2013(estimated landing date)	
JTMD-BF-313	post-and-beam wood	NT68	HI	Kauai: Donkey Beach	2015 March 22	
JTMD-BF-315	post-and-beam wood	NT70	HI	Kauai: Hanamaula Beach	2013 November 9	
JTMD-BF-316	post-and-beam wood	NT71	WA	Moclips	2013 spring (estimated landing date)	
JTMD-BF-317	post-and-beam wood	NT72	WA	Moclips	2013 spring(estimated landing date)	
JTMD-BF-318	post-and-beam wood	NT73	WA	Moclips	2013-14(estimated landing date)	
JTMD-BF-319	post-and-beam wood	NT74	WA	Moclips	2013-14(estimated landing date)	

JTMD-BF-320	post-and-beam wood	NT75	WA	Moclips	2013-14(estimated landing date)	
JTMD-BF-321	post-and-beam wood	NT76	WA	Grayland	2014 spring (estimated landing date)	
JTMD-BF-322	post-and-beam wood	NT77	WA	Queets	2014 October (estimated landing date)	
JTMD-BF-323	post-and-beam wood	NT78	WA	Ocean Shores	2014 spring (estimated landing date)	
JTMD-BF-324	post-and-beam wood	NT80	WA	Ocean Shores	2013 fall (estimated landing date)	
JTMD-BF-325	post-and-beam wood	NT81	WA	Ocean Shores	2013 fall (estimated landing date)	
JTMD-BF-326	post-and-beam wood	NT82	WA	Ocean Shores	2013 fall (estimated landing date)	
JTMD-BF-327	milled log	NT83	WA	Oysterville	2013 spring (estimated landing date)	
JTMD-BF-328	tray	JWC #50, yellow tray	WA	Long Beach	2015 early April to May 26	Yes
JTMD-BF-329	vessel hull	Kohanaiki Vessel, , 20'	HI	Kohanaiki	2015 14 February	Yes
JTMD-BF-330	buoy	Strawberry Point foam buoy 16"x20" WDFW 539	WA	Strawberry Point, south of La Push	2015 February 25	Yes
JTMD-BF-331	vessel	Oysterville boat fragment:第三寿丸 (Dai-San-Kotobuki-Maru) (The Third Celebration)	WA	Long Beach: Oysterville	2014 March 14	
JTMD-BF-332	lid	Long Beach lid JWC27, light blue	WA	Long Beach	2015 early April to May 26	
JTMD-BF-333	pot	Long Beach brown pot JWC38	WA	Long Beach	2015 early April to 26 May	

JTMD-BF-334	urchin tray	Long Beach green urchin tray JWC29	WA	Long Beach	2015 early April to May 26	
JTMD-BF-335	sieve	Long Beach blue circular sieve JWC15; urchin pot support disk	WA	Long Beach	2015 March 16 to April 1	
JTMD-BF-336	buoy	Long Beach black buoy 14"; JWC32	WA	Long Beach	2015 early April to May 26	
JTMD-BF-337	pipe	Long Beach blue pipe; JWC31	WA	Long Beach	2015 early April to May 26	
JTMD-BF-338	pallet	Second Beach pallet	WA	Second Beach ONP	2015 May 26	Yes
JTMD-BF-339	vessel	Queets vessel WDFW 706-709	WA	ONP Queets	2015; sighted May 8 by USCG; onshore May 16	Yes
JTMD-BF-340	pallet	Wouwer pallet	BC	Wouwer Island	2015 March 29	
JTMD-BF-341	buoy, fishing	Second Beach buoy	WA	Second Beach ONP	2015 May 22	Yes
JTMD-BF-342	buoy	Second Beach crab [mis-written, meant: "FAD" ?] buoy	WA	Second Beach ONP	2015 May 22	
JTMD-BF-343	basket	Debris #50, white basket	WA	Long Beach	2015 March 16 to April 1	
JTMD-BF-344	crate	Cape Perpetua crate	OR	South of Yachats	2015 April 7	
JTMD-BF-345	frame	Long Beach frame	WA	Long Beach	2014 week of December 29	
JTMD-BF-346	basket	Waikiki Washington blue basket	WA [not HI]	Waikiki Beach	2015 April 1	
JTMD-BF-347	buoy	Quail Street black buoy large	OR	Quail Street, Seal Rock	2015 April 14	Yes
JTMD-BF-348	buoy	Quail Street black buoy imploded	OR	Quail Street, Seal Rock	2015 April 14	
JTMD-BF-349	tank	fish tank	WA	Copalis Beach	2015 April 14	Yes
JTMD-BF-350	sieve	Moclips pink sieve #2	WA	Moclips	2015 April 14	
JTMD-BF-352	vessel	Long Beach vessel / Ilwaco north	WA	Long Beach	2015 March 29	Yes

JTMD-BF-353	tote	Moclips blue tote	WA	Roosevelt Beach, Moclips 47.1722 x 124.19536	2015 April 5	
JTMD-BF-354	tote	Ocean Park blue tote 1 mussel rec'd June 2016	WA	Long Beach near Ocean Park	2015 April 3	
JTMD-BF-355	crate	Moclips blue crate fragment	WA	Roosevelt Beach, Moclips 47.1722 x 124.19536	2015 April 6	
JTMD-BF-356	vessel	Seal Rock / Ona Beach vessel 26'	OR	off Seal Rock / Ona Beach	2015 April 9 sighted April 6	Yes
JTMD-BF-357	buoy	WA orange buoy	WA	La Push: change to: Ocean Shores 47.53138 x 124.353	(2013)	
JTMD-BF-358	tray	Queets green plastic tray	WA	ONP Queets	2015 April 9	Yes
JTMD-BF-359	tote	Long Beach blue plastic tank	WA	Long Beach	2015 April 13	
JTMD-BF-360	tote	Long Beach Grass Roots	WA	Long Beach	2015 April 25	
JTMD-BF-361	basket	Long Beach Grass Roots basket	WA	Long Beach	2015 April 25	
JTMD-BF-362	tote	tote WDFW 560	WA	Oysterville	2015 July 29	
JTMD-BF-363	bowl	WDFW 555, plastic bowl	WA	Oysterville	2015 February 26	Yes
JTMD-BF-364	container (carboy)	plastic	WA	Oysterville	2015 May 8	
JTMD-BF-365	basket/crate	WDFW 557	WA	Ocean Shores	2015 July 5	
JTMD-BF-366	plastic-metal boom	WDFW 558 40 feet	WA	Kayostia Beach	2015 July 15	
JTMD-BF-367	tote (crate) piece	yellow tote piece WDFW561	WA	Oysterville	2015 July 29	Yes
JTMD-BF-368	lid	white lid #30	WA	Long Beach	2015 May 18	
JTMD-BF-369	tote fragment	JWC33: blue tote fragment 24 lb with sand, 17 lb clean	WA	Long Beach	2015 early April to May 26	Yes
JTMD-BF-370	rebar cap	yellow rebar cap JWC37	WA	Long Beach	2015 early April to May 26	
JTMD-BF-371	eel trap	JWC47	WA	Long Beach (Seaview)	2015 early April to May 26	

JTMD-BF-372	tray (tote)	JWC42, pink tray (tote)	WA	Long Beach	2015 early April to May 26	
JTMD-BF-373	tote fragment	JWC43, white tote fragment	WA	Long Beach	2015 early April to May 26	
JTMD-BF-374	tote	JWC45, red Coca Cola 24 bottle tote	WA	Long Beach	2015 early April to May 26	
JTMD-BF-375	top	JWC46, blue plastic top	WA	Long Beach	2015 early April to May 26	
JTMD-BF-376	tote	JWC48, pastry tote	WA	Seaview (Long Beach)	2015 May 25	
JTMD-BF-377	pan	JWC49, pale yellow pan	WA	Long Beach (Seaview)	2015 early April to May 26	
JTMD-BF-378	tote fragment	JWC52, red tote fragment	WA	Long Beach (Seaview)	2015 early April to May 26	
JTMD-BF-379	tote fragment	JWC53, blue tote fragment	WA	Long Beach (Seaview)	2015 early April to May 26	
JTMD-BF-380	tote fragment	JWC55, blue tote fragment	WA	Long Beach (Seaview)	2015 early April to May 26	
JTMD-BF-382	crate	Ocean Beach blue crate	CA	Ocean Beach, south of San Francisco	2015 May 26	Yes
JTMD-BF-383	crate	JWC18, plastic crate	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-384	basket	debris 18, shallow white basket	WA	Long Beach	2014 December 25; sampled March 5, 2015	
JTMD-BF-386	buoy	JWC20, black buoy 14"	WA	Long Beach	2015 March 16–April 1	Yes
JTMD-BF-387	metal frame	green and white long metal frame debris#20 sieved	WA	Long Beach	2014 December 25	Yes
JTMD-BF-388	basket fragment	debris#19 sieved, orange basket fragment	WA	Long Beach	2014 December 25	
JTMD-BF-389	basket	debris #30 sieved, shallow white basket	WA	Long Beach	2014 December 25	
JTMD-BF-390	propeller	debris #29 sieved; black propeller	WA	[Long Beach area]	2015 January–March	
JTMD-BF-391	cylinder	debris #23 sieved; notched black cylinder	WA	[Long Beach area]	2015 January–March	

JTMD-BF-392	cutting board	sample #14, cutting board	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-393	tub	sample #17, gray tub	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-395	crate	sample #23, , blue crate	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-396	pallet /helmet	pallet (Pt. Grenville) /helmet (Moclips)	WA	Pacific Beach // Moclips-Pt. Grenville area	2014 April 14	
JTMD-BF-397	dock piece	WDFW662, dock piece (660-671 all = BF 397)	WA	Long Beach: Klipsan Approach	2015 May 1	
JTMD-BF-398	octopus trap	JWC sample 24, octopus trap	WA	[Long Beach area]	2015 March 16–April 1	Yes
JTMD-BF-400	mirror cover	JWC Sample 51, mirror cover	WA	Long Beach	2015 early April–May 26	
JTMD-BF-401	buoy	WDFW 562, black buoy	WA	Kalaloch Beach	2015 August 7	
JTMD-BF-402	vessel	WDFW Seaview Boat AKA Ilwaco Boat	WA	Seaview	2015 May 10	Yes
JTMD-BF-403	buoy	WDFW658, Kalaloch buoy WDFW 660 and 659?	WA	Kalaloch	2015 April 25, 27	
JTMD-BF-404	buoy	buoy (black collapsed buoy / float)	OR	Kissing Rock Beach	2015 August 25	
JTMD-BF-405	basket	basket	WA	Long Beach	2015 March 16–April 1	Yes
JTMD-BF-406	basket	Waikiki Beach basket	WA [not HI]	Waikiki Beach	2015 March 16–April 1	Yes
JTMD-BF-407	bucket	Chapman25, blue basket	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-408	basket	Chapman 16, white basket	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-409	tote (crate)	Chapman21, white tote (crate)	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-410	basket	no tracking #, green basket	OR	off Newport; same event as 573 and 574: off Heceta Head	2015 February 10	Yes
JTMD-BF-411	basket	no tracking #, white basket	OR	off Newport; same event as 573 and 574: off Heceta Head	2015 February 10	

JTMD-BF-412	basket	white broken basket, Debris #53	WA	Long Beach	2015 March 16–April 1	
JTMD-BF-413	basket	white basket	WA	Long Beach	2015 January–March	
JTMD-BF-414	basket	blue round tall basket	WA	Long Beach	2014 December 25	Yes
JTMD-BF-415	plastic piece (fragment)	white plastic piece (fragment)	WA	Long Beach	2015 January--February	
JTMD-BF-416	milled log	NT88	OR	Newport: South Beach	2013 spring (collected June 1, 2013; est. landing date is spring 2013)	
JTMD-BF-417	tote	S304 plastic tote	OR	recovered offshore: assume about 20 mi offshore of Newport	2015 February 25	
JTMD-BF-418	tote	JWC44 white tote	WA	Long Beach	2015 May 26	
JTMD-BF-419	post-and-beam wood	NT91	OR	Cape Blanco	2013-14	
JTMD-BF-420	boat panel fragment	NT92	WA	Long Beach (Oysterville)	2015 May–June	
JTMD-BF-421	post-and-beam wood	NT93	HI	Kauai: Kealia Point	2014	
JTMD-BF-422	post-and-beam wood	NT94	OR	Bandon	2014 May 22	
JTMD-BF-423	pallet	blue pallet	OR	Gold Beach: Bailey Beach	2015 May 14	
JTMD-BF-424	laundry basket	red laundry basket	OR	Crook Point, south of Gold Beach	2015 March 28	
JTMD-BF-425	golf caddy leg	Ja-Ru golf caddy robot leg	OR	Crook Point, south of Gold Beach	2015 April 17	
JTMD-BF-426	tray	black tray	WA	Queets	2015 April 9	
JTMD-BF-427	plastic bar	black plastic bar	OR	Cape Arago: South Cove	2015 May 28	
JTMD-BF-428	float	black round float	WA	Long Beach (Oysterville)	2015 April 11	
JTMD-BF-429	tray	white tray	WA	Queets	2015 April 9	

JTMD-BF-430	tray	black plastic tray	WA	Ocean Shores 47.53138 x 124.353	2014	
JTMD-BF-433	bucket	yellow bucket	OR	Kissing Rock Beach, north of Gold Beach	2014 December 16	
JTMD-BF-434	post-and-beam wood	post-and-beam NT95	CA	Doran Spit, Bodega Bay	2015 November 3	
JTMD-BF-435	bin	blue bin / blue tote	WA	Long Beach (Surfside and north)	2015 November 4	
JTMD-BF-436	tray	large white tray bread tray	WA	Long Beach: north of Oysterville Approach	2015 November 5	
JTMD-BF-437	tote	orange tote	WA	Long Beach: near Oysterville approach	2015 November 5	
JTMD-BF-438	float	black plastic float	WA	Long Beach: Leadbetter Point	2015 May 8	
JTMD-BF-439	float	brown plastic float	WA	Long Beach: Leadbetter Point	2015 May 29	
JTMD-BF-440	buoy	buoy	OR	Beverly Beach	2015 December 16	
JTMD-BF-441	basket fragment	yellow basket fragment	OR	2 miles south of Coquille Point, Bandon	2015 week of November 2	
JTMD-BF-442	buoy	black-brown buoy	WA	Long Beach	2015 November 14	
JTMD-BF-443	tote	blue tote	WA	Long Beach	2015 December 9	
JTMD-BF-444	tote	yellow tote	WA	Long Beach	2015 December 14	
JTMD-BF-445	buoy?	white buoy?	WA	Long Beach	2015 December 15	
JTMD-BF-446	tote	white tote	WA	Long Beach	2015 December 17	
JTMD-BF-447	tote	blue bottle tote	WA	Long Beach	2015 December 22	
JTMD-BF-448	rope on container	rope remnant on 5 gallon blue plastic container	WA	Long Beach: Leadbetter Point	2015 December 22	
JTMD-BF-449	vessel	Moclips vessel, 32'	WA	Moclips	2014 (sic) May 29	Yes
JTMD-BF-450	post-and-beam wood	Long Beach post-and-beam	WA	Long Beach	[2013] 2015 December 23	

JTMD-BF-451	buoy	Nye Beach buoy	OR	Nye Beach	2015 December 26	
JTMD-BF-452	orange buoy	Long Beach orange buoy; Russ Lewis 006	WA	Long Beach	2015 December 24	
JTMD-BF-453	post-and-beam wood	Waimalano p&b/NT96	HI	Oahu: Waimalano Bay	2015 May–August	
JTMD-BF-454	styrofoam-wood panel	Long Beach styro-wood panel; JWC25	WA	Long Beach	2015 between early April and end of May; sampled May 27	
JTMD-BF-455	buoy	14" Copalis black buoy	WA	Copalis Beach	2015 April 3	Yes
JTMD-BF-456	ring	Bandon black plastic ring	OR	Bandon	2015 December 20	
JTMD-BF-457	basket	Manzanita white basket (half) #1	OR	Manzanita [Tillamook County]	2015 February 28	
JTMD-BF-458	fish box	blue plastic commercial fish box	WA	Long Beach	2015 April 15	Yes
JTMD-BF-459	buoy	WDFW 721	WA	Ocean Shores	2015 December 4	
JTMD-BF-460	plastic piece	WDFW 726	WA	Ocean Shores	2015 December 4	
JTMD-BF-461	basket	Manzanita blue baskets one of 2 blue baskets of this date and location; other is 570	OR	Manzanita [Tillamook County]	2015 February 28	
JTMD-BF-462	float (buoy)	Long Beach black float	WA	Long Beach	2015 January 4	
JTMD-BF-463	tray	Queets green planting tray	WA	ONP Queets	2015 April 9	
JTMD-BF-464	tote	Queets white bottom tote WDFW 731	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-465	basket	Queets yellow basket fragment WDFW 733	WA	Queets (ditto 464 details)	2015 December 16	
JTMD-BF-466	crate	beer bottle crate	OR	Devils Punchbowl State Natural Area	2015 January 23	
JTMD-BF-467	tote	sample #35	WA	Long Beach	2015 early April to May 26	

JTMD-BF-468	pallet	"Korean pallet"	WA	3 miles north of Oysterville (Jesse Schultz)	2014 (sic) March 13	
JTMD-BF-469	tote	WDFW 729	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-470	white basket	WDFW735	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-471	line	WDFW 736	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-472	tote	WDFW 732; blue top tote	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-473	crate	WDFW 730	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-474	tote	grey tote WDFW 728	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-475	yellow basket	WDFW 734	WA	Queets [Quinault Reservation south of Queets River mouth)	2015 December 16	
JTMD-BF-476	tote	old blue tote	WA	Long Beach: near Leadbetter Point	2015 December 25	
JTMD-BF-477	buoy		WA	La Push to Kalaloch	2015 May 10	
JTMD-BF-478	buoy		WA	La Push to Kalaloch	2015 May 24	
JTMD-BF-479	buoy		WA	La Push to Kalaloch	2015 May 24	
JTMD-BF-480	buoy		WA	La Push to Kalaloch	2015 July	
JTMD-BF-481	float (glass)		WA	Long Beach	2015 December 24	
JTMD-BF-482	ball of nylon rope	NT: MpW462015-2; rec'd June 2016	WA	Roosevelt Beach, Moclips	2015 April 6	
JTMD-BF-483	post-and-beam wood	NT98	OR	Cape Lookout 45.36350 x 123.97057	2014 retrieved 1-17-16	

JTMD-BF-485	post-and-beam wood	NT100	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-19-16	
JTMD-BF-486	post-and-beam wood	NT101	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-19-16	
JTMD-BF-487	post-and-beam wood	NT102	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-20-16	
JTMD-BF-488	post-and-beam wood	NT103	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-20-16	
JTMD-BF-489	post-and-beam	NT104	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-20-16	
JTMD-BF-490	post-and-beam wood	NT105	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-20-16	
JTMD-BF-491	post-and-beam wood	NT106	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-20-16	
JTMD-BF-492	post-and-beam wood	NT107	WA	Oysterville 46.63135 x 124.07090	2013 retrieved 1-20-16	
JTMD-BF-493	boat panel	NT108	WA	Oysterville 46.63135 x 124.07090	2015 Spring–summer; retrieved December 2015	
JTMD-BF-494	post-and-beam wood	NT109	OR	Pistol River, Gold Beach	2013 retrieved 1-26-16	
JTMD-BF-495	wood: painted with metal fastenings; dock section?	NT110	OR	Bandon	2014 May 22	
JTMD-BF-496	basket	large blue basket	WA	Long Beach	2016 January 29	
JTMD-BF-497	jet ski	Hawaii ID # DAR 447 = should be 477 per labels	HI	Oahu: Laie	2016 January 25	Yes
JTMD-BF-498	tote	plastic tote blue tote 2 mussels rec'd Oysterville Beach approach; 015	WA	Long Beach	2016 February 11	
JTMD-BF-499	buoy	brown plastic floats; two tied together	WA	Long Beach	2016 February 15	
JTMD-BF-500	tote	Saporo beer tote	WA	Long Beach	2016 February 16	

JTMD-BF-501	tree	NT111; tree is 8 feet long (roots and lower part of trunk); Japanese black pine	WA	Long Beach	2016 February 18	
JTMD-BF-502	float	yellow float	WA	Long Beach	2016 February 20	
JTMD-BF-503	float	black float, plastic says Inaba Kasen on it JWC 898	WA	Long Beach: Leadbetter Point	2016 February 20	
JTMD-BF-504	plastic cap	Kure black plastic spray cap	CA	Salmon Creek Beach, Bodega Bay	2016 March 5	
JTMD-BF-505	buoy	12" float: black 2-eared buoy with rope: SANSHIN Lewis #18	WA	Long Beach	2016 March 7	
JTMD-BF-506	styrofoam float	foam cylinder float with rope harness 017	WA	Long Beach: Leadbetter Point	2016 March 7	
JTMD-BF-507	buoy	white float (plastic)	OR	Tillamook Bay: Bay Ocean Peninsula	2016 March 7	
JTMD-BF-508	crate	white crate	OR	Arch Cape	2016 February 19	
JTMD-BF-509	styrofoam float	large weathered white styrofoam float; styrofoam "log"; Russ Lewis 820	WA	Long Beach	2016 March 7	
JTMD-BF-510	buoy		WA	Ocean Shores 47.53138x124.353	2015 January 10	
JTMD-BF-511	buoy	orange float	WA	Ocean Shores 47.53138x124.353	(2012–2015)	
JTMD-BF-512	buoy	orange float	WA	Ocean Shores 47.53138x124.353	(2012–2015)	
JTMD-BF-513	buoy	black float	OR	Kissing Rock, Gold Beach 42.362x124.42448	2015 December 21	
JTMD-BF-514	buoy	pink float	OR	Tillamook: South Jetty	2016 January 16	
JTMD-BF-515	buoy	float: "black float blow co. with rope"	OR	Bandon: Mars Street	2015 December 22	
JTMD-BF-516	plastic bar	red plastic bar	OR	Tillamook: South Jetty	2016 January 16	
JTMD-BF-517	crate	yellow Kirin beer bottle crate	OR	Cape Blanco, south near Eel River 42.82883x124.5506	2015 December 28	
JTMD-BF-518	buoy	large black plastic float	WA	Long Beach: Leadbetter	2016 March 14	

JTMD-BF-519	container	blue container; sample #819	WA	Long Beach	2016 March 7	
JTMD-BF-520	buoy	orange float	OR	Tillamook Bay: Bay Ocean Peninsula	2016 March 14	
JTMD-BF-521	tote	blue tote JWC 822	OR	Nye Beach	2016 March 14	Yes
JTMD-BF-522	buoy, orange	South Beach float orange float 2 ears 12" diameter JWC #900	OR	South Beach, Yaquina Bay area	2016 March 16	
JTMD-BF-523	child's shoe	Pistol River shoe	OR	Pistol River, south of Gold Beach	2016 March 21	
JTMD-BF-524	broom handle	Myers Creek handle	OR	Myers Creek, Gold Beach	2016 March 3	
JTMD-BF-525	dust pan	Yachats melted pan: Japanese "silver model A" fide A. Isobe	OR	Yachats	2016 ca. March 16	
JTMD-BF-526	vessel	Horsfall Beach Vessel 16' vessel: Vessel ID #: 730 265 105 44 7556	OR	1.5mi N of Horsfall Beach, N of Coos Bay	2016 March 22	Yes
JTMD-BF-527	pot	Hubbard's Creek cooking pot	OR	Hubbard's Creek, N of Gold Beach	2016 March 24	
JTMD-BF-528	tray	Hubbard's Creek tray	OR	Hubbard's Creek, N of Gold Beach	2016 March 24	
JTMD-BF-529	buoy	Hubbard's Creek float with rope	OR	Hubbard's Creek, N of Gold Beach	2016 March 24	
JTMD-BF-530	vessel fragment		OR	Hubbard's Creek, N of Gold Beach	2016 March 24	
JTMD-BF-531	styrofoam buoy	white cylindrical styrofoam float, 41cmLx28cmD; Fawn and Michael Custer (notebook 34, p. 26; #739)	OR	Quail St., Seal Rock	2016 March 25	Yes
JTMD-BF-532	vessel	20' vessel from Iwate Prefecture: IT 3-37322	WA	South of Kalaloch	2016 March 26	Yes
JTMD-BF-533	vessel	Lincoln City boat; AKA Roads End boat, 14' stern fragment JWC 890	OR	Roads End, Lincoln City: 1 block N of path leading to beach from turn-around next to Road's End parking	2016 March 27 (on beach)	Yes
JTMD-BF-534	tote	plastic white bottle tote	WA	Long Beach: 2 miles South of Leadbetter	2016 March 25	
JTMD-BF-535	rope	Long Beach rope	WA	Long Beach	2016 April 3	

JTMD-BF-536	tote	Long Beach tote	WA	Long Beach	2016 April 5	
JTMD-BF-537	tote		OR	South of Winchester Bay	2016 April 15	
JTMD-BF-538	vessel	Sixes River vessel	OR	mouth of Sixes River	2016 April 16	Yes
JTMD-BF-539	milled log	Douglas fir log #1	HI	Kauai: Kealia Beach	2016 April 7	
JTMD-BF-540	milled log	Douglas fir log #2	HI	Kauai: Kealia Beach	2016 April 10	
JTMD-BF-541	tote, broken		WA	Long Beach	2016 April 15 or 17	
JTMD-BF-542	post and beam wood		WA	Long Beach	2016 April	
JTMD-BF-543	buoy, black		OR	Seal Rock Quail Street beach	2016 April 18	
JTMD-BF-544	dish rack		OR	Seal Rock Quail Street beach	2016 April 18	
JTMD-BF- 545	vessel		OR	mouth of the Umpqua River	2016 March 26	
JTMD-BF-546	barrel fragment	blue plastic barrel fragment 839	OR	Moolack Beach Bridge	2016 April 29	
JTMD-BF-547	pink basket		WA	Long Beach	2016 May 14	
JTMD-BF-548	orange float		WA	Long Beach	2016 May 16/17	
JTMD-BF-549	blue tote		WA	Long Beach	2016 May 16/17	
JTMD-BF-550	yellow float		WA	Long Beach	2016 May 16/17	
JTMD-BF-551	gray tote, gray flat		WA	Long Beach	2015 September–December	
JTMD-BF-553	pink pot		WA	Long Beach	December 2015 to January 2016	
JTMD-BF-554	white plastic object		WA	Pacific Beach	2015 12 April	
JTMD-BF-555	vessel	Daini Katsu Maru HI DAR 318	HI	Oahu: Alan Davis Beach	2015 April 22	Yes

JTMD-BF-556	bucket lid	Bd1142016-2 green cracked	OR	Bandon: Mars St.	2016 January 14	
JTMD-BF-557	crate	CPS3262016-14 blue crate fragment	OR	Crook Point South Gold Beach	2016 March 26	
JTMD-BF-558	basket fragment	CPS3262016-10	OR	Crook Point South Gold Beach	2016 March 26	
JTMD-BF-559	float, black		OR	Crook Point South Gold Beach	2016 March 26	
JTMD-BF-560	hollow black bar	CPS 3262016-1	OR	Crook Point South Gold Beach	2016 March 26	
JTMD-BF-561	crate, white, fragment		OR	Bandon	2015 November 6	
JTMD-BF-562	collapsed styrofoam float with rope		OR	Pistol River,Gold Beach	2016 March 18	
JTMD-BF-563	basket	pink basket, #54	WA	Long Beach	2015 April 2	
JTMD-BF-564	lid	pink lid #55	WA	Long Beach	2015 April 2	
JTMD-BF-565	basket	basket fragment #56	WA	Long Beach	2015 April 2	
JTMD-BF-566	plastic lid	#32	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-567	buoy	black buoy #11	WA	Long Beach	2015 February 25–27	
JTMD-BF-569	bowl	white bowl #1 group A	OR	Manzanita	2015 February 28	
JTMD-BF-570	basket	blue basket #2 group A one of 2 blue baskes of this date and location; other is 461	OR	Manzanita	2015 February 28	
JTMD-BF-571	basket	shallow white rectangular basket #6	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-572	bumper piece	black bumper piece #22	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-573	basket	blue no #	OR	off Heceta Head	2015 February 10	
JTMD-BF-574	basket	orange no #	OR	off Heceta Head	2015 February 10	

JTMD-BF-575	basket	green #27	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-576	jug	white jug #8	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-577	basket	white #10	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-578	basket	#3	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-579	float	#16 small blue	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-580	basket	yellow plastic, fragment #28	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-581	bowl	white dog #25	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-582	lid	pink #4	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-583	piece	yellow plastic #7	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-585	cylinder	black plastic #17	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-586	shelving	black plastic #14	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-587	basket	shallow white #9	WA	Long Beach	2015 December 14–March 15	
JTMD-BF-588	lid	green #5 "Mauser" embossed on lid "Debris #5"	WA	Long Beach	2015 February 25–27	
JTMD-BF-589	2-eared black buoy	Moolack/Beverly buoy	OR	Moolack-Beverly Beach	2016 June 15	
JTMD-BF-590	pink/orange float	Crook Point float	OR	Crook Point	2016 March 16	
JTMD-BF-591	tote	Mosquito Creek float	WA	La Push: Mosquito Creek, Olympic National Park, at landing site of BF-8	2015 April 21	
JTMD-BF-592	basket	blue basket fragment	OR	Bandon: Mars Street	2016 January 14	
JTMD-BF-593	tote	broken tote	WA	Long Beach	2016 April 16	
JTMD-BF-594	tote	green tote	WA	Long Beach (Leadbetter)	2016 February 1	

JTMD-BF-595	tote	blue tote	WA	Long Beach (Leadbetter)	2016 February 1	
JTMD-BF-596	crate		OR	Lane County: Bob Creek Wayside	2015 April 19	
JTMD-BF-597	blue tote		WA	North Ocean Park	2016 January 24	
JTMD-BF-598	floats	2 attached black plastic floats 899	WA	Long Beach: Leadbetter	2016 February 16	
JTMD-BF-599	basket	blue fish basket	WA	Long Beach	2015 April 26	
JTMD-BF-600	bottle cap	Crook Point bottle cap	OR	Crook Point South	2016 June 15	
JTMD-BF-601	float	black float	OR	Crook Point South	2016 June 15	
JTMD-BF-602	tire	Yokohoma wheel and tire	OR	Crook Point South	2016 June 17	
JTMD-BF-603	tote	Beard's Hollow tote	WA	Beard's Hollow, south of Long Beach	2015 May 16	
JTMD-BF-604	beer crate	Long Beach beer crate / bottle rack	WA	Long Beach	2016 rec'd May 6	
JTMD-BF-605	orange plastic float	large orange plastic float	WA	Long Beach: Leadbetter Point	2015	
JTMD-BF-606	float	brown basketball size float	WA	Long Beach	2015 March 8	
JTMD-BF-607	float	styrofoam float	WA	Surfside	2015 May 17	
JTMD-BF-608	float	small plastic tote	WA	Long Beach: near Ocean Park	2015 April 15	
JTMD-BF-609	float	black float 023	WA	Long Beach: Leadbetter	2016 March 15	
JTMD-BF-610	tote	yellow tote	WA	Long Beach: Leadbetter	2015 14 May	
JTMD-BF-611	float	pale big orange plastic float with a big hole in it	WA	WA: 3 miles north of Long Beach	2015 13 May	
JMTD-BF-612	float	small round float and we have the float	WA	Long Beach: Leadbetter	2016 March 16	
JTMD-BF-613	float	beige plastic float; JWC 897	WA	Long Beach: Leadbetter	2016 February 19	

JTMD-BF-614	basket	blue basket	OR	Lincoln Co.: Moolack Beach	2016 April 11	
JTMD-BF-615	float	brown float	WA	WA: 3 miles south of Leadbetter Point	2015 May 26	
JTMD-BF-616	plastic can fragment	large round blue plastic can fragment, #47	WA	Long Beach	2015 between May 27 and September 8	
JTMD-BF-617	fiberglass foam piece		WA	QIN South Queets QIN = Quinault Indian Reservation	2015 May 21	
JTMD-BF-618	buoy	orange buoy	WA	Long Beach: Seaside dumpster	2016 January 12	
JTMD-BF-619	float	orange plastic float	WA	Long Beach: Leadbetter Point	2015 December 24	
JTMD-BF-621	float	rope float	WA	Long Beach: Leadbetter Point	2015 December 22	
JTMD-BF-622	tote	plastic sake bottle tote	WA	Long Beach: Leadbetter Point	2015 December 25	
JTMD-BF-623	tote	blue tote	WA	Long Beach: Leadbetter Point	2015 December 24	
JTMD-BF-624	tote	blue tote with rope handles ex Don Sarver, photos JWC 558	OR	0.5 miles north of Yaquina Head light, Newport	2015 December 20	
JTMD-BF-625	pallet	green plastic pallet	WA	Long Beach	2015 June 2	
JTMD-BF-626	vessel fragment	Friendship House vessel	HI	on the rocky beach just north of Kapa'a on Kauai	2016 June 25	
JTMD-BF-627	post-and-beam wood	Kapa'a Beach p&b	HI	Kauai: Kapa'a Beach	2016 June 15	
JTMD-BF-628	post-and-beam wood	South beach p&b15	OR	Newport: South Beach	2013 (sic) April 24	
JTMD-BF-629	post-and-beam wood	South beach p&b27	OR	Newport: South Beach	2013 (sic) April 27	
JTMD-BF-630	post-and-beam wood	South beach p&b29	OR	Newport: South Beach	2013 (sic) April 27	
JTMD-BF-631	pallet	Roosevelt Beach blue pallet	WA	Grays Harbor County: Roosevelt Beach	2015 August 12	
JTMD-BF-632	tote	blue tote	OR	Seal Rock: Quail Street	2015 April 14	

JTMD-BF-633	post-and-beam wood	Waipake p&b 2013	HI	Kauai: Waipake Beach	2013 (sic) September 29	
JTMD-BF-634	buoy	black buoy, broken eared	OR	Newport: South Beach	2016 March 16	
JTMD-BF-635	float	black float	OR	Lincoln Co.: Moolack Beach	2016 May 17	
JTMD-BF-636	basket	basket #1 Manzanita	OR	Manzanita	2015 February 28	
JTMD-BF-637	tote	blue tote	OR	Moolack Beach	2015 April 8	
JTMD-BF-638	vessel	Sacchi Beach vessel	OR	Sacchi Beach	2016 April 23	
JTMD-BF-639	buoy	15.5" black buoy 2 ears	WA	Long Beach	2016 February 24–May 5	
JTMD-BF-640	tote	blue tote	OR	Agate Beach	2016 March 23	
JTMD-BF- 641	pallet		WA	Long Beach	2016 July 6	
JTMD-BF-642	tote	broken plastic tote	WA	Long Beach	2016 July 6	
JTMD-BF-643	float		WA	Long Beach	2016 March 15	
JTMD-BF-645	buoy	12" black buoy	WA	Long Beach	2016 collected between January and May	
JTMD-BF-646	bucket	bucket #1	OR	Manzanita	2015 February 28	
JTMD-BF-647	float	brown float	WA	Long Beach: Leadbetter Point	2016 March 15	
JTMD-BF-648	drain lid	metal vessel deck drain lid	OR	Crook Point South	2016 March 26	
JTMD-BF-649	jug	white plastic jug	OR	Moolack/Beverly Beach	2016 April 10	
JTMD-BF-650	table	small folding plastic table	WA	Long Beach	2016 July 10	
JTMD-BF-651	tree	tree	OR	Nye Beach	2016 July 13	
JTMD-BF-652	vessel	Falcon Cove boat	OR	Falcon Cove	2016 July 20	

JMTD-BF-653	yellow navigation buoy	Kahuku buoy DAR 506 / HI59	HI	Kahuku, Oahu	2016 March 13	
JTMD-BF-654	buoy	HI 60	HI	Kailua, Hawaii	2016 March 11	
JTMD-BF-655	fishing bin	NWHI HI61	HI	HI: Papahanaumokuakea MNM (Marine National Monument), found at sea	2015 June 1 take as 6-1-15	
JTMD-BF-656	plastic jug	Otter Crest jug	OR	Otter Crest	2016 March 26	
JTMD-BF-657	buoy	imploded buoy	WA	Long Beach	2015 April–May	
JTMD-BF-658	pallet	So. Beach pallet	OR	South Beach	2016 October 5	
JTMD-BF-659	crate	blue plastic crate fragment	WA	Long Beach	2015 May	
JTMD-BF-660	tire (wheel)	Long Beach wheel	WA	Long Beach	2014 no date	
JTMD-BF-661	buoy	black buoy	HI	Big Island (Hawai'i Island): offshore South Kona, south of Honokohau Harbor	2016 November 17	
JTMD-BF-662	crate	Kamilo Point blue crate	HI	Big Island (Hawai'i): Kamilo Point	2016 November 19	
JTMD-BF-663	tote fragment	blue tote fragment	WA	Long Beach	2016 November 8	
JTMD-BF-664	buoy	Long Beach turquoise buoy	WA	Long Beach	2016 November 30	
JTMD-BF-665	buoy	black buoy	WA	Long Beach	2016 December 1	
JTMD-BF-666	crate	green crate (box) called "pallet" in correspondence and (in part) in NOAA database	CA	Daly City: Mussel Rock Beach	2015 (sic) July 25	
JTMD-BF-667	rope and buoy mass	rope mass with about 100 floats: Hi-Zex Float, Sanshino Kako Co., Ltd., Oyama Blow Ind Co. Ltd	HI	Kauai Kapa'a UTM 4Q 467554.96E 2441508.99N	2016 December 7	Yes

JTMD-BF-668	tube	black tube, about 13" long split	OR	Bandon: on the beach N 43.088001 W 124.435364	2016 March 15	
JTMD-BF-669	sieve	black, open ended, <6"	OR	Bandon: on the beach	2016 March 15	
JTMD-BF-670	pot	plant pot -- orange / brown; SU-35 Sanko, <6"	OR	Bandon: on the beach	2016 March 15	
JTMD-BF-671	tubing	gray tubing, small	OR	Bandon: on the beach	2016 March 15	
JTMD-BF-672	lid	brown square lid, "Nestle", small	OR	Bandon: on the beach	2016 April 18	
JTMD-BF-673	tote	blue tote #41	WA	Long Beach	2015 May 27–September 15	
JTMD-BF-674	plastic piece	yellow plastic #49	WA	Long Beach	2015 May 27–September 15	
JTMD-BF-675	vessel	MG3-38403, 18'	HI	Oahu: Waimanalo	2016 December 22	
JTMD-BF-676	crate fragment		OR	Bandon	2016 December 15	
JTMD-BF-677	vessel		HI	Big Island (Hawai'i): southeast coast on DHHL lands	2017 January 16	

Appendix 7-2. Scientists contributing to JTMD taxonomic effort

Scientist	Affiliation / Institution	Taxon	Common Name
Bjorn Altermark	University of Tromso	Teredinidae	shipworms
Claudia Arango	Queensland Museum, Australia	Pycnogonida	sea spiders
David Bilderback	Bandon, Oregon	Bryozoa	bryozoans
Luisa M. S. Borges	Portugal (now Helmholtz-Zentrum Geesthacht, Germany)	Teredinidae	shipworms
Stephen Cairns	Smithsonian Institution (NMNH)	Scleractinia	corals
Dale Calder	Royal Ontario Museum	Hydrozoa	hydroids
James T. Carlton	Williams College	General; Mollusca; Cirripedia	barnacles, mollusks
Benny Chan	Academia Sinica, Taiwan	Cirripedia: *Chthamalus*	barnacles
John W. Chapman	Oregon State University	Amphipoda, Isopoda, Tanaidacea; Decapoda	amphipods, isopods, tanaids, crabs
Henry Choong	Royal Ontario Museum; Fairbanks Museum, St. Johnsbury, VT	Hydrozoa	hydroids
Eugene V. Coan	Santa Barbara Museum of Natural History	Bivalvia	clams and oysters
Jeffery R. Cordell	University of Washington	Copepoda	copepods
Natalia Demchenko	Zhirmunsky Institute, Vladivostok, Russia	Caprellidae	skeleton "shrimp"
Matthew Dick	Hokkaido University	Bryozoa	bryozoans
Anthony Draeger	Kensington CA	Polyplacophora	chitons
Douglas Eernisse	California State University, Fullerton	Lottidae, Nacellidae, Siphonariidae, Polyplacophora	limpets, chitons
David Elvin	Shelburne, Vermont	Porifera	sponges
Neal Evenhuis	Bishop Museum	Chironomidae	marine flies
Daphne Fautin	University of Kansas	Anthozoa	sea anemones
Kenneth Finger	University of California, Berkeley	Foraminifera	foraminiferans
Aaron Gann	Oregon State University	Pisces: *Seriola*	yellowtail amberjack
Jonathan Geller	Moss Landing Marine Laboratories	Barcoding and metagenomics	many groups
Scott Godwin	NOAA Honolulu	General	several groups
Terry Gosliner	California Academy of Sciences, San Francisco	Opisthobranchia	sea slugs
Takuma Haga	Toyohashi Museum of Natural History, Toyohashi	Bivalvia	clams, oysters, scallops
Gayle Hansen	Oregon State University	Algae	seaweeds
Takeaki Hanyuda	Kobe University	Algae	seaweeds
Niels-Viggo Hobbs	University of Rhode Island	Isopoda: *Ianiropsis*	isopods
Leslie Harris	Los Angeles County Museum of Natural History	Polychaeta	worms
John Holleman	Merritt College	Platyhelminthes	flatworms
Gyo Itani	Kochi University	Decapoda	crabs
Colin Johnson	Harvard University	Bryozoa: *Tricellaria*	bryozoans
Hiroshi Kajihara	Hokkaido University	Nemertea	ribbon worms
Hiroshi Kawai	Kobe University	Algae	seaweeds

Gerald Krantz	Oregon State University	Halacaridae	marine mites
Elena Kupriyanova	Australian Museum	Serpulidae	tube worms
Gretchen Lambert	University of Washington	Ascidiacea	sea squirts
Katrina Lohan	SERC	bivalve parasites	parasites
Konstantin Lutaenko	Zhirmunsky Institute, Vladivostok, Russia	Mytilidae	mussels
Josh Mackie	California State University, San Jose	Bryozoa	bryozoans
Christopher Mah	Smithsonian Institution (NMNH)	Asteroidea	sea stars
Svetlana Maslakova	University of Oregon Institute of Marine Biology	Nemertea	ribbon worms
Gary McDonald	University of California, Santa Cruz	Opisthobranchia	sea slugs
James H. McLean	Los Angeles County Museum of Natural History	Gastropoda	snails
Richard Mooi	California Academy of Sciences	Echinoidea	sea urchins
Bruce Mundy	NOAA NFMS	Pisces: *Oplegnathus*	barred knifejaw
Eijiroh Nishi	Yokohama National University	Annelida	serpulid *Spirobranchus*
Teruaki Nishikawa	Nagoya University	Sipuncula	peanut worms
Peter Ng	National University of Singapore	Decapoda	crabs
Michio Otani	Osaka Museum of Natural History	Cirripedia	barnacles
David Pawson	Smithsonian Institution (NMNH)	Holothuroidea	sea cucumbers
Erik Pilgrim	EPA National Exposure Research Laboratory	Lottidae, Nacellidae, Siphonariidae, Polyplacophora	limpets, chitons
Michael Raupach	Deutsches Zentrum für Marine Biodiversitätsforschung	Teredinidae	shipworms
Gregory Ruiz	Smithsonian Institution (SERC)	bivalve parasites	haplosporidians, hydrozoa, crustacea
J. Reuben Shipway	Northeastern University	Teredinidae	shipworms
Ashleigh Smythe	Virginia Military Institute	Nematoda	roundworms
Ichiro Takeuchi	Ehime University	Caprellidae	skeleton "shrimp"
Hayato Tanaka	Hiroshima University	Ostracoda	ostracods
Nancy Treneman	University of Oregon Institute of Marine Biology	Teredinidae	shipworms
Paul Valentich-Scott	Santa Barbara Museum of Natural History	Bivalvia	clams and oysters
Moriaki Yasuhara	University of Hong Kong	Ostracoda	ostracods

Appendix 7-3. JTMD Biodiversity: Master species list as of January 30, 2017

CHROMISTA
- **Rhizaria**
  - **Foraminifera**
    - *Cibicides lobatulus*
    - *Elphidium crispum*
    - *Elphidium hannai*
    - *Bolivina seminuda*
    - *Cornuspira planorbis*
    - *Dyocibicides biserialis*
    - *Miliolinella subrotundata*
    - *Nonionella stella*
    - *Planogypsina squamiformis*
    - *Planorbulina acervalis*
    - *Rosalina globularis*
    - *Trochammina cf. T. hadai*
    - Arenaceous/agglutinating, unidentified
  - **Cercozoa**
    - *Gromia "oviformis"*
- **Ciliophora**
  - **Suctoria**
    - Species A (yellow)
    - Species B (white)
  - **Folliculinidae**
    - Unidentified species (2+ species)
  - **Vorticellidae**
    - *Vorticella* sp.
  - **Zoothamniidae**
    - *Zoothamnium* sp.

PORIFERA
- *Callyspongia murex*
- Chalinidae, unidentified species
- *Clathrina coriacea*
- *Cliona* sp.
- *Halichondria* sp. A
- *Halichondria* sp. B
- *Halichondria* sp. C
- *Halichondria panicea*
- *Hymenciadon sinapium*
- *Leucandra* sp.
- *Leucosolenia eleanor*
- *Leucosolenia variabilis*

Mycale macginitei
Sycon raphanus
Sycon sp. A
Sycon sp. B
Sycon sp. C
Ute sp.

CNIDARIA
Hydrozoa
Thecata
Abietinaria sp.
Aglaophenia lophocarpa
Amphisbetia furcata
Antenella sp.
Bougainvillia muscus?
Campanulinidae, unidentified
Clytia cf gracilis
Clytia cf linearis
Eutima japonica
Halecium tenellum
Halecium cf. beani
Hydrodendron gracile
Obelia longissima
Opercularella sp.
Orthopyxis caliculata
Orthopyxis platycarpa
Phialella sp.
Plumaleciidae, undetermined
Plumularia setacea
Plumularia caliculata
Plumularia sp.
Sertularella sp. A
Sertularella mutsuensis
Stylactaria sp.
Athecata
Sarsia sp.
Unidentified
Anthozoa
Actiniaria
Metridium dianthus
Anthopleura asiatica
Diadumene lineata
?Urticina sp.
Actinaria sp. A
Actinaria sp. B
Scleractinia
Pocillopora damicornis

NEMATODA
- Unidentified species (3+)

NEMERTEA
- Lineidae, unidentified species
- *Quasitetrastemma nigrifrons*
- *Oerstedia dorsalis*
- Unidentified species

PLATYHELMINTHES
- Rhabditophora
  - Tricladida
  - Uteriporidae? Unidentified species
  - Unidentified species (2+)
- Monogenea
  - *Benedenia seriolae*

SIPUNCULA
- *Phascolosoma scolops*

ANNELIDA
- **Oligochaeta**
  - Unidentified species (2+)

- **Polychaeta**
  - **Nereidae**
  - *Nereis pelagica*
  - *Perinereis nigropunctata*
  - **Phyllodocidae**
  - *Eulalia quadrioculata*
  - *Eulalia viridis*-complex
  - *Eteone* sp.
  - *Nereiphylla* sp. *cf. N. castanea*
  - **Polynoidae**
  - *Halosydna brevisetosa*-complex
  - *Harmothoe imbricata*
  - *Lepidonotus* sp.
  - **Syllidae**
  - *Syllis elongata*-complex
  - *Syllis hyalina*-complex
  - *Syllis* sp. *cf. S. ehlersoides*
  - *Syllis* sp. *cf. S. farallonensis*
  - *Syllis* sp. *cf. S. pulchra*
  - *Syllis gracilis*-complex
  - Syllinae species 1, 2, 3, 4, 5, 6
  - *Sphaerosyllis* sp.
  - *Trypanosyllis zebra*?
  - *Amblosyllis speciosa*-complex

Terebellidae
Amphitrite sp.
Terebella sp.
Oenonidae
Arabella semimaculata
Arabella iricolor-complex
Onuphidae
Unidentified species
Spionidae
Polydora sp.
Pygospio californica
Orbiniidae
Naineris sp.
Chrysopetalidae
Unidentified species
Paleanotus sp.
Acrocirridae
Acrocirrus sp.
Fabriciidae
Unidentified species
Sabellariidae?
Unidentified species
Sabellidae
Amphiglena sp.
Serpulidae
Hydroides ezoensis
Pomatoceros sp. *cf. P. minutus* (= *Spirobranchus minutus*)
Salmacina sp.?
Spirobranchus polytrema
Spirorbidae
Unidentified species (3+)

MOLLUSCA
Gastropoda
Lottiidae
Nipponacmea habei
Lottia species H
Lottia dorsuosa
Lottia tenuisculpta
Lottia cf. tenuisculpta
Lottia sp. TN2016
Nacellidae
Cellana grata
Cellana toreuma
Calyptraeidae
Crepidula onyx

Vermetidae
Serpulorbis sp.
Columbellidae
Mitrella moleculina
Mitrella sp. A (axial sculpture)
Muricidae
Reishia bronni
Pulmonata
Siphonariidae
Siphonaria sirius
Siphonaria japonica
Nudibranchia
Dolabella auricularia
Hermissenda crassicornis
Dendronotus frondosus
Eubranchus sp.
Unidentified species

Bivalvia
Mytilidae
Mytilus galloprovincialis
Mytilus coruscus
Mytilus trossulus
Modiolus nipponicus?
Modiolus kurilensis?
Modiolus sp. B
Modiolus sp. A
Modiolus comptus?
Musculus cupreus
Musculus sp. A
Mytilisepta virgata (= Septifer virgatus)
Lithophaga curta
Anomiidae
Anomia cytaeum Gray, 1850 *sensu* Huber, 2010: 617
Gryphaeidae
Hyotissa numisma (= *Hyotissa inaequivalvis*)
Hyotissa chemnitzi (= *Parahyotissa quercinus*; = *Parahyotissa* n. sp. of Huber)
Ostreidae
Crassostrea gigas
Dendostrea folium (= *Dendostrea affinis*)
Montacutidae
Mysella sp.?
Spondylidae
Spondylus cruentus (= *Spondylus squamosus*)
Arcidae
Arca navicularis
Arca sp. A
Arca sp. B

Barbatia fusca
Pectinidae
Scaeochlamys squamata
Laevichlamys irregularis
Pascahinnites coruscans (= Bractaechlamys coruscans)
Mizuhopecten yessoensis (= *Patinopecten yessoensis*)
Pectinidae species C
Pectinidae species A
Limidae
Limaria hakodatensis
Pteriidae
Pteria sp.
Pinctada imbricata (*cf.* Japanese clade *fucata*)
Pinctada margaritifera
Pinctada chemnitzii
Isognomon cf. ephippium
Malleidae
Malleus cf. irregularis
Chamidae
Chama sp. A (smooth internal margin)
Chama sp. (crenulated internal margin)
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 defilippii
Acanthochitona rubrolineata
Placiphorella stimpsoni

CRUSTACEA
Copepoda
Harpacticus sp.- *flexus* group
Harpacticus pacificus
Harpacticus septentrionalis
Harpacticus nicacensis
Parastenhelia spinosa

- *Tisbe* (2 spp.)
- *Paralaophonte congenera*
- *Paralaophonte* sp.
- *Sarsamphiascus minutus*
- *Sarsamphiascus varians* group
- *Heterolaophonte discophora*
- *Parathalestris intermedia*
- *Paramphiascella fulvofasciata*
- Laophontidae (unidentified species)
- *Dactylopodamphiascopsis latifolius*

Ostracoda

- *Sclerochilus verecundus*
- *Sclerochilus* sp.
- *Xestoleberis setouchiensis*
- *Obesotoma setosum*
- *Obesotoma* sp.
- Paradoxostomatidae

Cirripedia

- *Megabalanus rosa*
- *Megabalanus zebra*
- *Semibalanus cariosus*
- *Balanus crenatus*
- *Balanus glandula*
- *Balanus trigonus*
- *Chthamalus challengeri*
- *Pseudoctomeris sulcata*

Amphipoda

- **Ischyroceridae**
- *Jassa marmorata*-complex
  - (includes *staudei*, *slatteryi*)
- **Ampithoidae**
- *Ampithoe valida*
- *Ampithoe lacertosa*
- *Ampithoe koreana*
- **Stenothoidae**
- *Stenothoe crenulata*-complex
  - (includes *dentirama, gallensis)*
- **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 japonicus

ACARINA
Halacaridae
Halacarellus schefferi

BRYOZOA
Cheilostomatida
Aetea cf. anguina
Aetea cf. truncata
Biflustra grandicella
Biflustra irregulata
Biflustra sp. A
Arbocuspis cf. bellula
Bugula sp.
Callopora craticula
Candidae, undetermined
Catenicella elegans
Cauloramphus spinifer
Cauloramphus sp. A
Celleporaria brunnea
Celleporella "hyaline"
Celleporina porosissima
Celleporina umbonata

Celleporina cf. globosa
Conopeum nakanosum
Cribrilina mutabilis
Cryptosula pallasiana
Drepanophora cf gutta
Escharella hozawai
Exochella tricuspis
Fenestrulina orientalis
Membranipora villosa
Metroperiella cf biformis
Microporella borealis
Microporella neocriboides
Microporella luellae
Rhynchozoon sp.
Schizoporella japonica
Scruparia ambigua
Smittoidea spinigera
Tricellaria inopinata
Watersipora mawatarii
Watersipora subatra

Cyclostomatida
Borgiola sp.
Crisia cf. operculata
Crisidia sp.
Disporella cf. novaehollandiae
Entalophora sp.
Filicrisia franciscana
Proboscina sp.
Stomatopora sp.
Tubulipora misakiensis
Tubulipora pulchra

Ctenostomatida
Alcyonidium sp.
Walkeria prorepens

KAMPTOZOA
Barentsia sp.

ECHINODERMATA
Asteroidea
Asterias amurensis
Aphelasterias japonica
Patiria pectinifera
Echinoidea
Temnotrema sculptum

Holothuroidea
Havelockia versicolor

CHORDATA
Ascidiacea
Didemnum vexillum
Diplosoma sp.
Herdmania cf. pallida
Unidentified species

PISCES
Oplegnathus fasciatus
Seriola aureovittata

Oceanic – Neustonic Acquisitions via Larval or Planktonic Recruitment (PELAGIC)

CNIDARIA
Hydrozoa
Obelia griffini
ANNELIDA
Polychaeta
Amphinome rostrata
CRUSTACEA
Amphipoda
Caprella andreae
Cirripedia
Lepas spp.
Conchoderma auritum
Decapoda
Planes major
Plagusia immaculata
Plagusia squamosa

MOLLUSCA
Gastropoda
Fiona pinnata
Bivalvia
Teredora princesae
Uperotus clava

BRYOZOA
Cheilostomata
Jellyella tuberculata
Jellyella eburnea

Arbopercula angulata
    (= Electra tenella)

Oceanic – Neustonic Acquisitions: Entrainment (i.e., Passive Physical Entanglement) (PELAGIC)

RHIZARIA
- **Foraminifera**
  - *Globigerina bulloides*
  - *Globigerina uvula*
- **Radiolaria**
  - Unidentified

CNIDARIA
- **Hydrozoa**
  - *Velella velella*

MOLLUSCA
- **Gastropoda**
  - Pteropoda (including *Clio*, *Cavolina, Limacina*)
  - Heteropoda, unidentified
  - *Janthina* sp.

CRUSTACEA
- **Ostracoda**
  - *Conchoecia* sp.
- **Euphausiacea**
  - Unidentified species

Eastern Pacific Near Shore Pelagic Acquisitions

CRUSTACEA
- **Amphipoda**
  - *Calliopius pacificus*
  - *Atylus tridens*

Eastern Pacific Acquisitions, Largely Nepionic (via Larval or Planktonic Recruitment)

ANNELIDA
- **Polychaeta**
  - Polynoidae

CRUSTACEA
- **Cirripedia**
  - *Balanus* sp., *cf. B. glandula*
  - *Balanus crenatus*
  - *Pollicipes polymerus*

- **Isopoda**
  - *Gnorimosphaeroma* sp.
  - *Idotea wosnesenskii*
  - *Idotea resecata*
- **Amphipoda**
  - *Ptilohyale littoralis*
  - *Parhyale* sp.

MOLLUSCA
- **Bivalvia**
  - *Mytilus* spp.
  - *Crassadoma gigantea*
  - *Adula californiensis*
  - *Hiatella arctica*

CHORDATA
- **Ascidiacea**
  - *Styela gibbsii*
  - *Pyura haustor*

Hawaiian Acquisitions

MOLLUSCA
- Nudibranchia, Bivalvia, Gastropoda

CRUSTACEA
- **Amphipoda**
  - *Hyale* sp.

Provenance Unknown

HAPLOSPORIDA
- Unidentified (3 spp.) in JTMD *Mytilus galloprovincialis*

Appendix 7-4. Unique Species Occurrences

JTMD-BF-	Phylum		Species
1	Cnidaria	Hydrozoa	*Phialella* sp.
1	Crustacea	Amphipoda	*Caprella cristibrachium*
1	Crustacea	Decapoda	*Oedignathus inermis*
1	Crustacea	Decapoda	*Hemigrapsus sanguineus*
1	Echinodermata	Asteroidea	*Asterias amurensis*
1	Echinodermata	Holothuroidea	*Havelockia versicolor*
1	Arthropoda	Insecta	*Telmatogeton japonica*
1	Kamptozoa	Kamptozoa	*Barentsia* sp.
1	Mollusca	Gastropoda	*Mitrella moleculina*
1	Mollusca	Gastropoda	*Nipponacmea habei*
1	Annelida	Polychaeta	*Acrocirrus sp.*
1	Annelida	Polychaeta	*Nereis pelagica*
1	Annelida	Polychaeta	*Eulalia quadrioculata*
1	Annelida	Polychaeta	*Arabella semimaculata*
1	Annelida	Polychaeta	*Naineris* sp.
1	Annelida	Polychaeta	*Amphitrite* sp.
1	Annelida	Polychaeta	*Terebella* sp.
1	Porifera	Porifera	*Mycale macginitei*
1	Porifera	Porifera	*Halichondia* sp. A
1	Porifera	Porifera	*Halichondia* sp. B
1	Nemertea	Nemertea	Unidentified species
8	Cnidaria	Hydrozoa	*Orthopyxis caliculata*
8	Crustacea	Cirripedia	*Pseudoctomeris sulcata*
8	Nemertea	Nemertea	*Tetrastemma nigrifrons*
12	Cnidaria	Hydrozoa	*Bougainvillia muscus*
12	Cnidaria	Hydrozoa	*Obelia longissima*
23	Porifera	Porifera	*Sycon* sp. C.
23	Cnidaria	Hydrozoa	*Orthopyxis platycarpa*
23	Cnidaria	Hydrozoa	*Hydrodendron gracile*
23	Cnidaria	Hydrozoa	*Stylacteria* sp.
23	Cnidaria	Hydrozoa	*Sarsia* sp.
23	Nemertea	Nemertea	*Oerstedia dorsalis*
23	Annelida	Polychaeta	*Amphiglena* sp.
23	Annelida	Polychaeta	*Syllis cf. ehlersoides*
23	Annelida	Polychaeta	Unidentified species
23	Bryozoa	Cheilostomatida	*Celleporina cf. globosa*
23	Ascidiacea	Ascidiacea	*Diplosoma* sp.
28	Echinodermata	Asteroidea	*Aphelasterias japonica*
32	Mollusca	Gastropoda	*Dolabella auricularia*
32	Annelida	Polychaeta	*Perinereis nigropunctata*
32	Mollusca	Gastropoda	*Cellana grata*
40	Mollusca	Bivalvia	*Mizhopecten yessoensis*
40	Sipuncula	Sipuncula	*Phascolosoma scolops*
40	Annelida	Polychaeta	*Unidentified species*
40	Bryozoa	Cheilostomatida	*Watersipora subatra*
40	Crustacea	Amphipoda	*Gammaropsis japonica*
130	Mollusca	Gastropoda	*Crepidula onyx*

131	Annelida	Polychaeta	*Pomatoceros minutus*
136	Cnidaria	Hydrozoa	*Clytia cf gracilis*
147	Mollusca	Bivalvia	*Chama* sp. A
160	Bryozoa	Cheilostomatida	*Cauloramphus* sp. A
168	Annelida	Polychaeta	*Eulalia viridis*
172	Annelida	Polychaeta	*Syllis cf pulchra*
201	Mollusca	Bivalvia	*Musculus* sp. A
205	Cnidaria	Anthozoa	*?Urticina* sp.
207	Porifera	Porifera	*Unidentified species*
208	Bryozoa	Cyclostomaida	*Crisidia sp.*
210	Bryozoa	Cheilostomatida	*Metroperiella cf. biformis*
212	Mollusca	Bivalvia	*Spondylus cruentus*
215	Bryozoa	Cheilostomatida	*Celleporina porosissima*
225	Mollusca	Bivalvia	*Pectinidae* sp. A
229	Porifera	Porifera	*Halichondria* sp. C
241	Nemertea	Nemertea	Unidentified species
290	Bryozoa	Cheilostomatida	*Rhynchozoon* sp.
290	Mollusca	Bivalvia	*Serpulorbis* sp.
293	Mollusca	Bivalvia	*Modiolus* sp. A
328	Cnidaria	Hydrozoa	*Unidentified species*
338	Bryozoa	Cheilostomatida	*Conopeum nakanosum*
341	Cnidaria	Hydrozoa	*Antenella* sp.
342	Cnidaria	Hydrozoa	*Abietinaria* sp.
356	Mollusca	Gastropoda	*Hermissenda crassicornis*
356	Mollusca	Gastropoda	*Eubranchus* sp.
356	Mollusca	Bivalvia	*Teredo navalis*
356	Pisces	Pisces	*Seriola aureovittata*
371	Mollusca	Bivalvia	*Mysella sp.*
371	Mollusca	Bivalvia	*Pectinidae* sp. C
382	Cnidaria	Hydrozoa	*Opercularella* sp.
382	Mollusca	Gastropoda	*Mitrella* sp. A
391	Bryozoa	Cheilostomatida	*Cauloramphus spinifer*
391	Bryozoa	Cheilostomatida	*Microporella luellae*
397	Mollusca	Polyplacophora	*Placiphorella stimpsoni*
402	Porifera	Porifera	*Ute sp.*
402	Cnidaria	Hydrozoa	*Halecium cf. beani*
402	Mollusca	Bivalvia	*Arca* sp. A
402	Mollusca	Bivalvia	*Barbatia fusca*
402	Mollusca	Bivalvia	*Laevichlamys irregularis*
402	Mollusca	Bivalvia	*Pascahinnites coruscus*
402	Mollusca	Bivalvia	*Limaria hakodatensis*
423	Annelida	Polychaeta	Unidentified species
425	Bryozoa	Cheilostomatida	*Drepanophora cf. gutta*
523	Ascidiacea	Ascidiacea	*Herdmania cf. pallida*
531	Crustacea	Decapoda	*Sphaerozius nitidus*
533	Bryozoa	Cyclostomatida	*Borgiola* sp.
533	Cnidaria	Hydrozoa	*Unidentified species*
538	Cnidaria	Hydrozoa	*Clytia linearis*
538	Bryozoa	Cyclostomatida	*Crisia cf. operculata*
558	Crustacea	Amphipoda	*Caprella drepanochir*

597	Bryozoa	Cheilostomatida	*Cribrilina mutabilis*
643	Mollusca	Gastropoda	*Cellana toreuma*
653	Mollusca	Bivalvia	*Modiolus* sp. B
655	Mollusca	Bivalvia	*Pinctada margaritifera*
657	Bryozoa	Cheilostomatida	*Microporella neocriboides*
661	Crustacea	Isopoda	*Ianiropsis derjugini*
667	Bryozoa	Cyclostomatida	*Entalophora* sp.
667	Bryozoa	Cyclostomatida	*Stomatopora* sp.
667	Cnidaria	Anthozoa	*Actinaria sp.* A
675	Cnidaria	Anthozoa	*Actinaria sp.* B
675	Crustacea	Amphipoda	*Trachypleustes* sp.

Appendix 7-5. Species arriving dead-only on JTMD

PORIFERA
Chalinidae, unidentified species

CNIDARIA
Anthozoa: **Scleractinia**
Pocillopora damicornis

ANNELIDA
Polychaeta
Sabellariidae?
Unidentified species
Serpulidae
Spirobranchus polytrema
Salmacina sp.

MOLLUSCA
Gastropoda
Serpulorbis sp.

Bivalvia
Lithophaga curta
Mysella sp.
Spondylus cruentus
Scaeochlamys squamata
Laevichlamys irregularis
Pascahinnites coruscans
Pectinidae species C
Pectinidae species A
Limaria hakodatensis
Pinctada margaritifera
Pinctada chemnitzii
Chama sp. A
Sphenia coreanica?
Teredo navalis

BRYOZOA
Arbocuspis bellula
Biflustra irregulata
Callopora craticula
Cauloramphus spinifer
Celleporaria brunnea
Celleporina porosissima
Celleporina umbonata
Celleporina cf. globosa
Celleporina sp.
Conopeum nakanosum

Crisidia sp.
Drepanophora gutta
Membranipora villosa
Microporella luellae
Microporella neocriboides
Rhynchozoon sp.
Schizoporella japonica
Stomatopora sp.

Appendix 7-6. Species on JTMD from southern waters (species occurring south of the Boso Peninsula)

Taxon	**Species**	**Range**	**First appearance**	
			Hawaiian Islands	**North America**
CNIDARIA: Anthozoa (sea anemones)	***Anthopleura asiatica***	Southern Japan and south to the Indian Ocean		2016
	Pocillopora damicornis	Southern Japan and south; subtropical and tropical		2015
ANNELIDA: Polychaeta (worms)	***Spirobranchus cf. polytrema***	Southern Japan and south		2014
	Salmacina sp.			2016
CIRRIPEDIA (barnacles)	***Pseudoctomeris sulcata***	south of Boso Peninsula		2012
AMPHIPODA (amphipods)	***Trachypleustes* sp.**	subtropical-tropical	2016	
DECAPODA: **Brachyura** (crabs)	***Sphaerozius nitidus***	Indo-West Pacific		2016
MOLLUSCA: Gastropoda (snails)	***Mitrella moleculina***	Boso Peninsula and south		2012
MOLLUSCA: Bivalvia (clams, scallops, pen shells, *et al.*)	***Chama* sp.** A (smooth internal margin)	southern Japan and south		2016
	Hyotissa sp., including *H. numisma (= H. inaequivalvis)* and *H. chemnitzi* (2 species)	southern Japan and south	2013	2013
	Arca navicularis	Boso Peninsula and south		2012
	Barbatia fusca	Kii Peninsula and south		2015
	Scaeochlamys squamata	Boso Peninsula and south		2015
	Laevichlamys irregularis	Boso Peninsula and south		2015
	Pascahinnites coruscans	Kii Peninsula and south		2015
	Dendostrea folium	Amami Islands and south	2016	2014
	Spondylus cruentus	Boso Peninsula to Okinawa		2014
	Limaria hakodatensis	(to Hokkaido, but on BF-402 with other southern bivalves, and thus doubtless acquired south of Boso)		2015
	***Pteria* sp.**	Boso and Kii Peninsulas and south	2013 (Midway)	
	Pinctada imbricata (fucata)	Izu Peninsula and south		2014

	Pinctada margaritifera	Kii Peninsula and south	2015	
	Pinctada chemnitzii	Suruga Bay and south	2015	
	Isognomon ephippium	Kii 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
BRYOZOA (bryozoans)	***Crisia cf. operculata***	warm temperate-subtropical		2016
	Arbocuspis cf. bellula	subtropical-tropical		2013
	Biflustra grandicella	South China Sea and south		2013
	B. irregulata	South China Sea, South Korea, and south		2013
	***Biflustra* sp. A**	subtropical-tropical		2013
	Drepanophora cf gutta	tropical		2015
	Metroperiella cf. biformis	East China Sea and south		2014
	Smittoidea spinigera	warm-temperate, subtropical	2013	2014
ASCIDIACEA (sea squirts)	***Herdmania cf. pallida***	subtropical, tropical		2016

THEME III – Rafting of Japanese Species

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 from the Great 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.

Introduction

The purpose of the genetic component of the ADRIFT (Assessing the Debris-Related Impact From Tsunami) project was to generate DNA sequences from taxonomically validated specimens and use these sequences in a program to detect Japanese species in 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 creation of baseline sequences for future investigations of the field environment or identification of individual samples. The objective of the genetic component was to obtain DNA sequences that can identify species associated with the Great Tsunami of 2011. The 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

Three 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, and 3) fouling panels suspended in Pacific North America and Hawaii. Specimens were collected from JTMD objects arriving in North America and Hawaii as described in the previous chapter (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 Williams College to be examined and sorted, and specimens or tissue subsamples were subsequently shipped to Moss Landing Marine Laboratories (MLML).


Photo credit: JaNUS Co

Samples in Japan were collected from fouling plate surveys. The surveys were conducted at several locations in the Tohoku coast. 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 (Figure 8-1) to more closely align with the timing of of the original tsunami event. All survey sites suffered serious damage by the tsunami after the Great East Japan Earthquake in 2011.

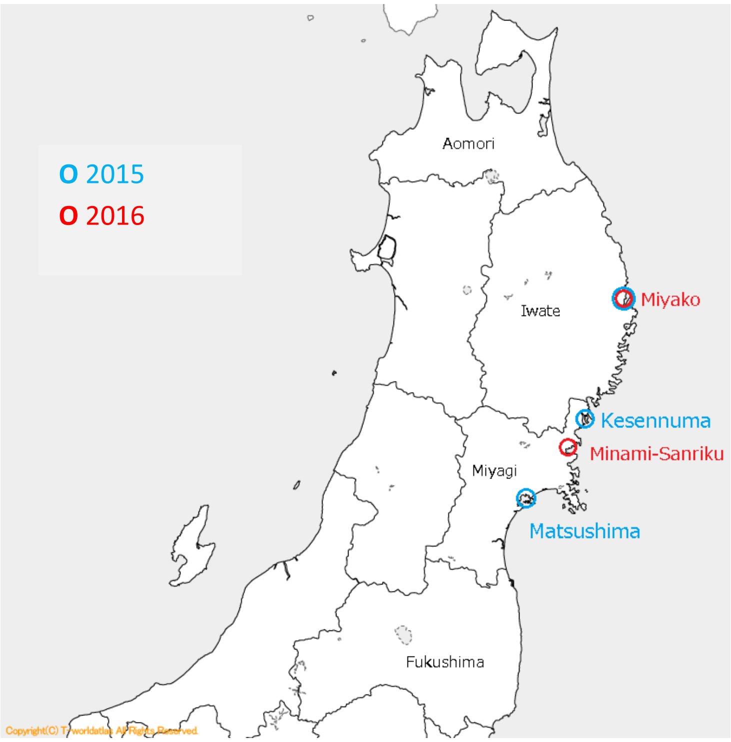


Figure 8-1. Fouling plate installation sites in 2015 (blue circles) and 2016 (red circles).

Fouling panels consisted of 14 cm square 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 processed and species identified morphologically, following the basic protocol used in North America (see Chapter 13 for more details). Detailed initial identification was conducted in a local laboratory and samples were preserved for DNA analysis and shipped to MLML.

Fouling plate samples from North America were obtained from fouling panels deployed at the following sites: San Francisco Bay CA, Humboldt Bay CA, Yaquina Bay OR, Willapa Bay WA, Grays Harbor WA, Neah Bay WA, Prince Rupert BC, and Ketchikan AK (see Chapter 13).

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

		Placement (# of plates)	1 month (# of retrieved plates)	3 month (# of retrieved plates)
2015	Miyako	Aug. 12th (30)	Sep. 8th (15)	Nov. 10th (15)
	Kesennuma	Aug. 4th (10)	Sep. 8th (5)	Nov. 11th (5)
	Matsushima	Jul. 24th (30)	Sep. 10th (15)	Nov. 12th (15)
2016	Miyako	Apr. 26th (30)	May. 31st (15)	Aug. 2nd (15)
	Minami-Sanriku	Apr. 26th (30)	Jun. 1st (14)	Aug. 3rd (15)

DNA extractions and PCR

DNA extractions of vouchers 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


Photo credit: JaNUS

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, NZ). 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.

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 clustered into OTU using USEARCH 1.8.

Results

JTMD voucher sequencing

In total, 294 specimens from JTMD were sequenced on the Ion Torrent PGM instrument. 191 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 the MLML invasive species database 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 results showing 94% or greater similarity to Genbank or MLML records were *Jassa marmorata*, *Ampithoe lacertosa*, *Semibalanus cariorus*, 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 is illustrated in Table 8-2. The numbers of morphological specimen and samples for DNA analysis are shown in Table 8-3. Number of species found was highest in Matsushima, and lowest in Minami-Sanriku. More species were detected in the three-month deployment survey than the one-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.

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

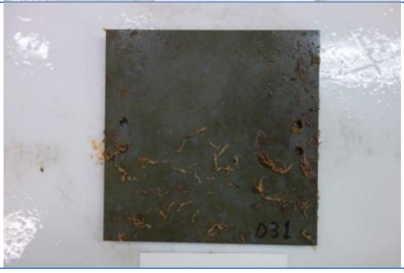
		The first survey (1 month)	**The second survey (3 months)**
2015	**Miyako**		
	Kesennuma		
	Matsushima		
2016	**Miyako**		
	Minami-Sanriku		

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

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.

Sequences from each putative morphospecies were aligned and phylogeneticaly 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 8-2. Maximum likelihood tree of COI sequences for specimens morphologically identified as Botryllidae, and one identified as *Aplidium*. Blue font surrounded by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

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).

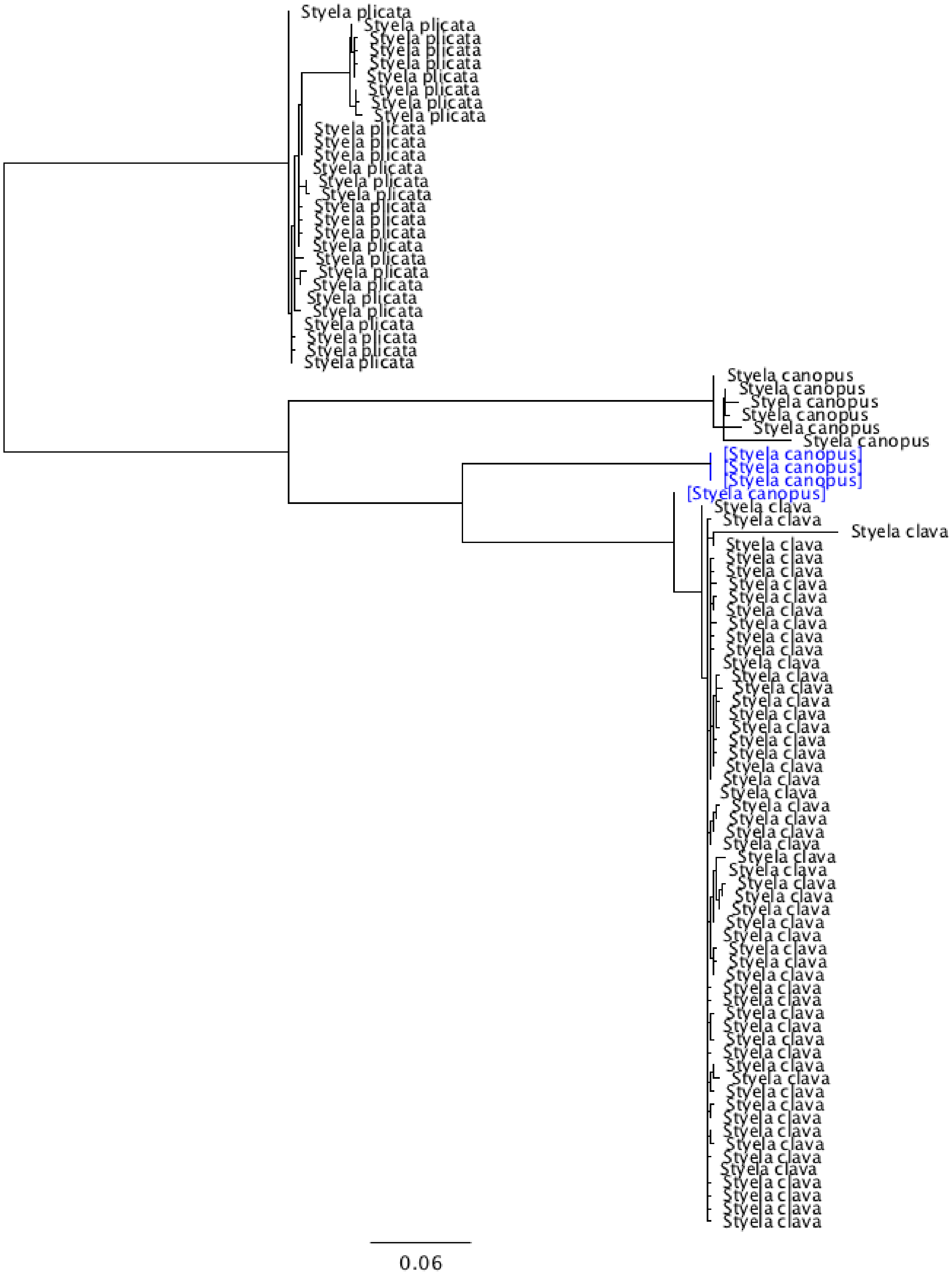


Figure 8-3. Relationships of Japanese specimens identified as *Styela canopus* to existing Genbank records. Blue font surrounded by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

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

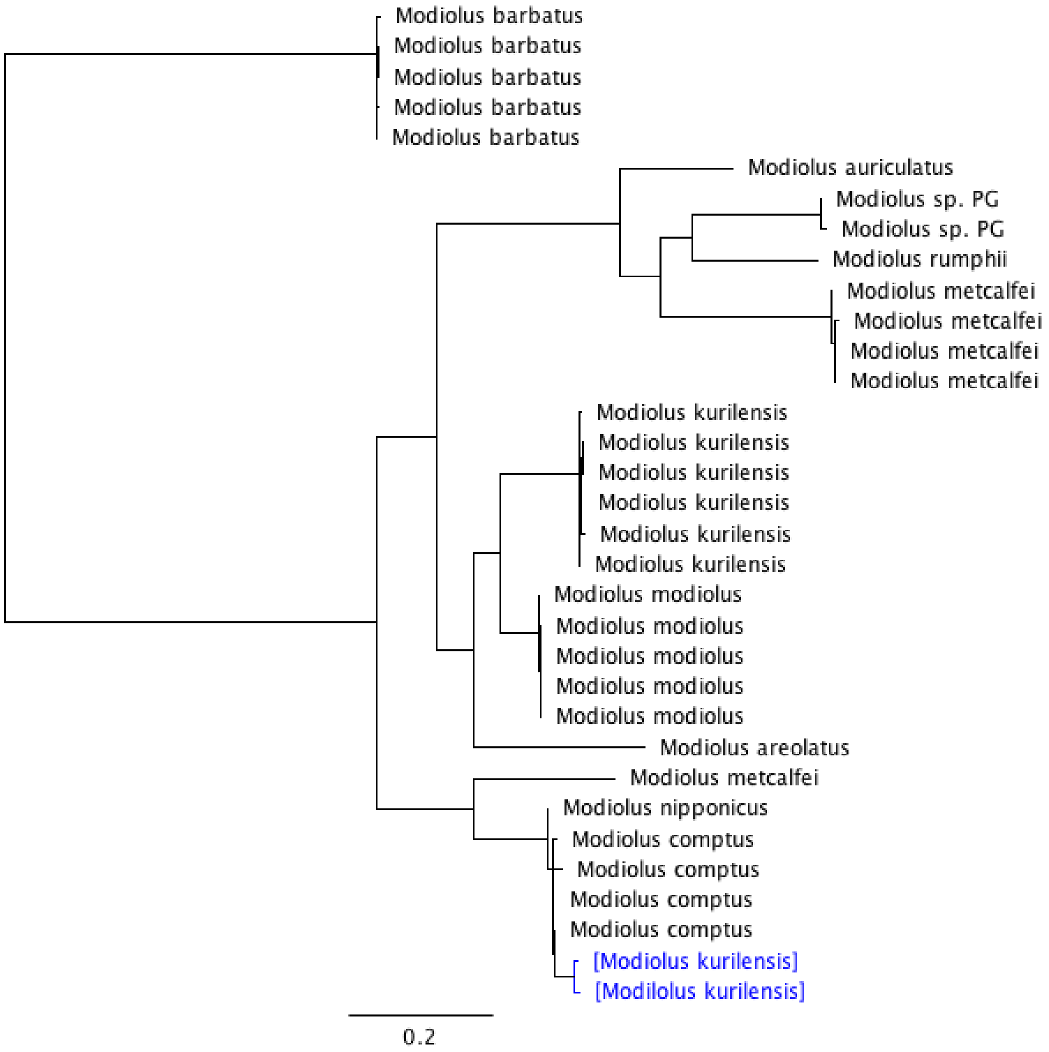


Figure 8-4. Specimens identified as *Modiolus kurilensis* are related to *M. nipponicus* or *M. comptus*. Blue font surrounded by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

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*.

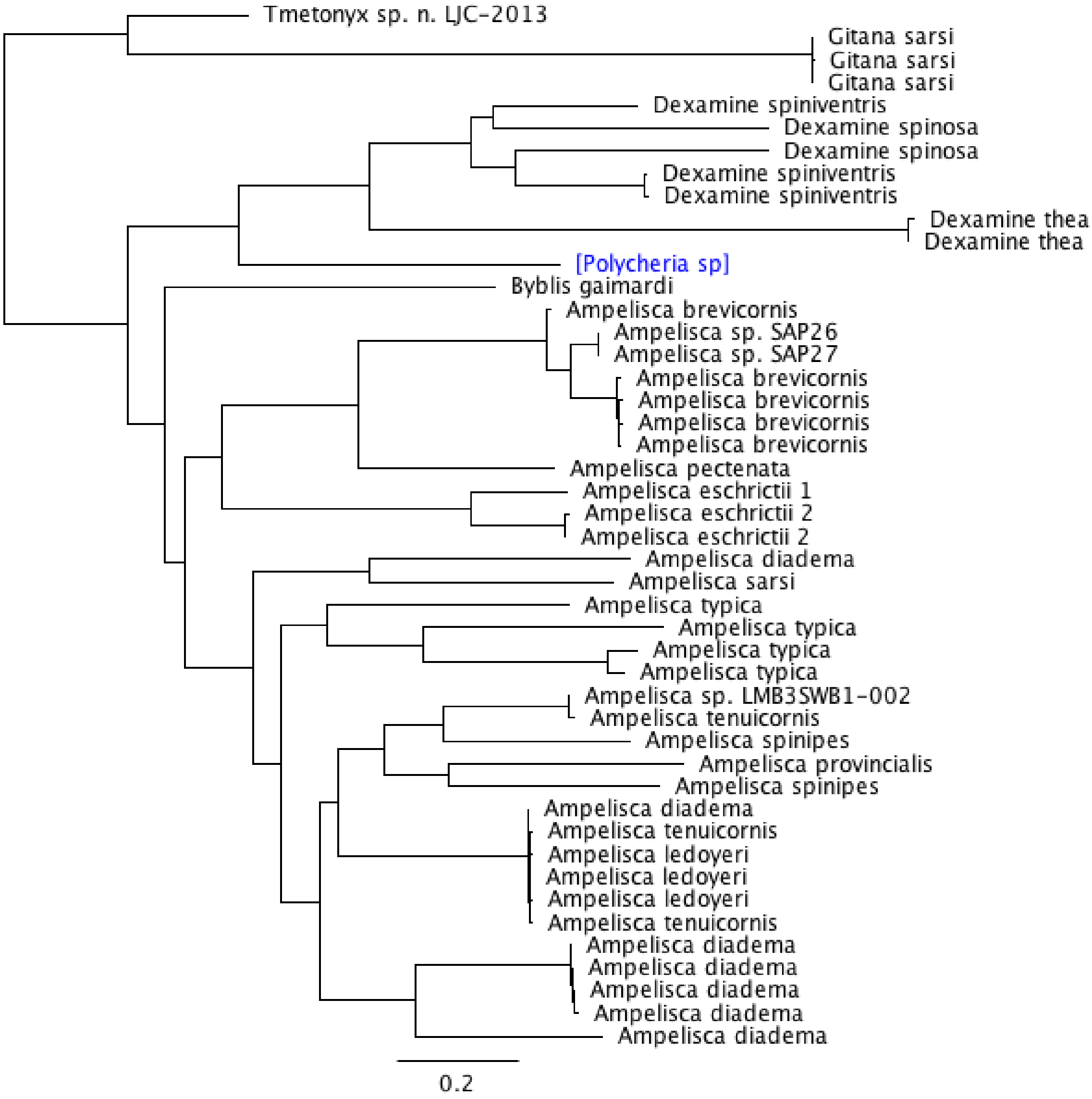


Figure 8-5. Morphologically identified *Polycheria* was phylogenetically basal to other Dexaminidae among the Gammaridea, and therefore this identification was accepted. Blue font surrounded by brackets indicates a Japanese fouling voucher; all other records are from Genbank or MLML database.

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 nonindigenous species *Mytilus galloprovincialis.*

99 plankton samples, 39 from British Columbia and 60 from Oregon and Washington, were received at MLML for DNA extractions for potential future PCR and sequencing-based detection of JTMD-associated species. 211,466 reads were analyzed with the 64 bit version of USEARCH 1.861 (Edgar 2015). Three sites in Yaquina Bay (Hog's Marina, Port of Newport, and Embarcadero) yielded 209 operational taxonomic units (OTU) from 64,972 paired-end reads of COI. These clustered into 209 OTU using a 97% similarity threshold, and OTUs matched Genbank at 95% or better for 66 OTU. Removing bacteria and unidentified phytoplankton left 63 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).

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	Bivalve	*Protoperidinium cf.*	Dinoflagellate
Hiatella sp.	Bivalvia	*Pyrocystis lunula*	Dinoflagellate
Kellia suborbicularis	Bivalvia	*Aplysiopsis enteromorphae*	Gastropoda
Melanochlamys diomedea	Bivalvia	*Assiminea grayana*	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	Bryachyura	*Gastropteron pacificum*	Gastropoda
Pandalus jordani	Caridea	*Hermissenda crassicornis*	Gastropoda
Amphibalanus improvisus	Cirrepedia	*Limacina helicina*	Gastropoda
Amphibalanus sp.	Cirrepedia	*Littorina plena*	Gastropoda
Balanus crenatus	Cirrepedia	*Lottia pelta*	Gastropoda
Balanus glandula	Cirrepedia	*Margarites pupillus*	Gastropoda
Chthamalus dalli	Cirrepedia	*Olivella biplicata*	Gastropoda
Pollicipes polymerus	Cirrepedia	*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	Copepoda	*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		

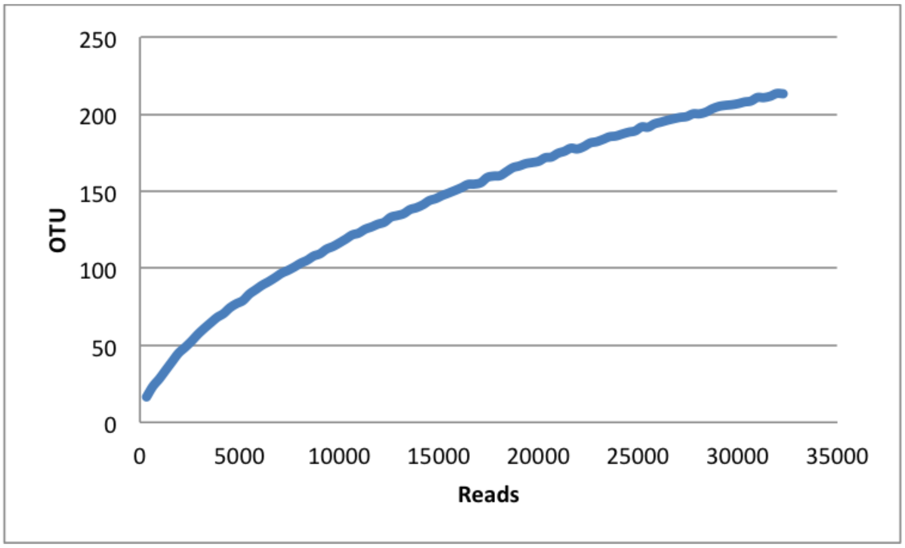


Figure 8-6. Yaquina Bay plankton. Rarefaction of OTUs recovered with increasing read abundance, using 165,809 unique reads, clustered at a 97% similarity threshold, and omitting any OTU with group size of 1 read.

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* in 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 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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Appendices

Appendix 8-1. Species 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	TENTACULATA	BRYOZOA	*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 achersicum*
10			*Ericthonius convexus*
11			*Jassa slatteryi*
12			*Paradexamine* sp.
13			*Polycheria* sp.
14			*Melita* sp.
15			*Leucothoe nagatai*
16			*Stenothoe* sp. 2
17			*Stenothoe* sp. 1
18			*Caprella equilibra*
19			*Caprella mutica*
20			*Caprella scaura*
21			*Paranthura japonica*
22			*Ianiropsis serricaudi*
23			*Synidotea hikigawaensis*
24			*Cymodoce japonica*
25			*Zeuxo* sp. (aff. *Z. coralensis*)
26	CHORDATA	ASCIDIACEA	*Diplosoma listerarium*
27			*Distaplia dubia*
28			Botryllidae gen. sp. 1
29			Botryllidae gen. sp. 2
30			Botryllidae gen sp. 3
31			Botryllidae gen sp. 4

The second survey			
	PHYLUM	CLASS	Species
1	PORIFERA	DEMOSPONGIAE	*Halichondria* sp.
2	CNIDARIA	HYDROZOA	*Halecium pusillum*
3	NEMERTINEA	ENOPLA	*Nemertellina yamaokai*
4	TENTACULATA	BRYOZOA	*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	*Hemilepidonotus helotypus*
13			*Anaitides* sp.
14			*Eularia 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 achersicum*
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			*Ascicia* sp.
47			*Botryllus schlosseri*
48			Botryllidae gen. sp. 1
49			Botryllidae gen. sp. 2
50			Botryllidae gen. sp. 3
51			*Styela* sp.

Identified species in Kesennnuma (Year 2)

	The first survey		
	PHYLUM	CLASS	Species
1	CNIDARIA	ANTHOZOA	*Diadumene lineata*
2	TENTACULATA	BRYOZOA	*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 serricaudi*
31			*Cirolana harfordi japonica*
32	CHORDATA	ASCIDIACEA	*Diplosoma listerianum*
33			Botryllidae gen sp. 1
34			Botryllidae gen sp. 2
35			*Symplegma reptans*

	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	TENTACULATA	BRYOZOA	*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		MAXILLOPODA	*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			*Cypsiphimedia 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*

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	TENTACULATA	BRYOZOA	*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	PYCNOGONIDEA	*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 serricaudi*
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			*Tridentiger trigonocephalus*

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	TENTACULATA	BRYOZOA	*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	PYCNOGONIDEA	*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			*Dynoides dentisinus*
65			*Eualus leptognathus*
66			*Heptacarpus rectirostris*
67			*Halicarcinus messor*
68			*Hemigrapsus takanoi*
69	CHORDATA	ASCIDIACEA	*Aplidium* sp.
70			*Didemnum* sp.
71			*Ciona intestinalis* type A
72			*Ciona savignyi*
73			*Ascidia sydneiensis*
74			*Ascidia zara*
75			Botryllidae gen. sp. 1
76			Botryllidae gen. sp. 2
77			*Styela canopus*
78			*Molgula manhattensis*
79		OESTEICHTHYES	*Tridentiger trigonocephalus*

Identified species in Miyako (Year 3)

	The first survey		
	PHYLUM	CLASS	Species
1	TENTACULATA	BRYOZOA	*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 achersicum*
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.

	The second survey		
	PHYLUM	CLASS	Species
1	PORIFERA	DEMOSPONGIAE	*Halichondria sp.*
2	NEMERTINEA	ENOPLA	*Nemertellina yamaokai*
3	TENTACULATA	BRYOZOA	*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			*Cymodoce 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.*

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*

The second survey

	PHYLUM	CLASS	Species
1	CNIDARIA	HYDROZOA	*Obelia sp. (almost hydranth lacking)*
2	NEMERTINEA	ENOPLA	*Nemertellina yamaokai*
3			*Tetrastemma nigrifrons*
4	TENTACULATA	BRYOZOA	*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			*Cymodoce 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

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

Specimen	**Morphological Assignment**	**Genetic result**
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 accept
M3_S-10.02	*Amathia distans*	Amathia distans provisionally accept
M3_S-10.03	*Amathia distans*	Amathia distans provisionally accept
M3_M-13.05	*Amphibalanus amphitrite*	*Amphibalanus amphitrite* confirm
M3_M-27.05	*Amphibalanus amphitrite*	*Caprella mutica*
M3_S-77.01	*Amphibalanus amphitrite*	*Amphibalanus amphitrite* confirm
M3_S-63.01	*Amphibalanus eburneus*	*Amphibalanus eburneus* confirm
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	*Ampothoe* sp1	*Fistulobalanus albicostatus*
M3_M-19.01-02	*Anaitides* sp.	Phyllocidae, 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 *Anooplodactylus 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 not near Aoroides columbiae
M3_S-43.02-06	*Aoroides longimerus*	*Aoroides longimerus* provisionally accepted but not near *Aoroides columbiae*
M3_M-24.01-04	*Aoroides* sp.	*Aoroides longimerus* provisionally accepted but not near *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*	*Arculatula senhousia* confirm (as *Musculista*)
M3_S-39.02	*Arcuatula senhousia*	*Arculatula senhousia* confirm (as *Musculista*)
M3_S-39.03	*Arcuatula senhousia*	*Arculatula senhousia* confirm (as *Musculista*)
M3_M-30.01	*Ascidia* sp.	Nemertean contaminant?
M3_M-35.02	*Ascidia* sp.	Nemertean contaminant?
M3_S-4.03	*Ascidia sydneiensis*	*Halichondria*, contaminant?
M3_S-4.05	*Ascidia sydneiensis*	unknown; contaminant?

M3_S-2.01	*Ascidia zara*	*Ascidea zara* confirm
M3_S-2.02	*Ascidia zara*	*Ciona savignyi*
M3_S-2.03	*Ascidia zara*	*Ascidea zara* confirm
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*
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* confirm
M16_M-40.2	*Botrylloides violaceus*	*Botrylloides violaceus* confirm
M16_M-40.3	*Botrylloides violaceus*	*Botrylloides violaceus* confirm
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 accept; near Pyramidellidae in Genbank tree
M3_S-26.01	*Bugula neritina*	*Bugula neritina* confirm (note cryptic species exist)
M3_S-26.02	*Bugula neritina*	*Bugula neritina* confirm (note cryptic species exist)
M3_S-26.03	*Bugula neritina*	*Bugula neritina* confirm (note cryptic species exist)
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 equililbra* confirmed
M3_M-11.02	*Caprella equilibra*	*Caprella equililbra* confirmed
M3_M-11.03	*Caprella equilibra*	*Caprella equililbra* 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 poroissima* provisionally accept
M3_M-14.02	*Celleporina Porosissima*	*Celleporina poroissima* provisionally accept
M3_M-14.03	*Celleporina Porosissima*	*Celleporina poroissima* provisionally accept
M16_M-18.1	*Celleporina porosissima*	*Celleporina poroissima* provisionally accept
M16_M-18.2	*Celleporina porosissima*	*Botrylloides violaceus*
M16_M-18.3	*Celleporina porosissima*	*Celleporina poroissima* provisionally accept
M16_MS-2.2	*Celleporina porosissima*	*Celleporina poroissima* provisionally accept
M16_MS-2.5	*Celleporina porosissima*	*Celleporina poroissima* provisionally accept
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 ambiguous but not *challengeri*
M3_S-1.01	*Ciona intestinalis* type A	*Ciona intestinalis* confirm
M3_S-1.02	*Ciona intestinalis* type A	*Ciona intestinalis* confirm
M3_S-1.03	*Ciona intestinalis* type A	*Ciona intestinalis* confirm
M3_S-3.01	*Ciona savignyi*	*Ciona savignyi* confirm
M3_S-3.02	*Ciona savignyi*	*Ciona savignyi* confirm
M3_S-3.03	*Ciona savignyi*	*Ciona savignyi* confirm
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 accept
M3_S-71.02-06	*Colomastix* sp.	*Colomastix* sp. provisionally accept
M3_S-30.01	*Crassostrea gigas*	*Crassostrea gigas* confirm
M3_S-30.02	*Crassostrea gigas*	*Crassostrea gigas* confirm
M3_S-30.03	*Crassostrea gigas*	*Crassostrea gigas* confirm
M3_S-34.01	*Cymodoce japonica*	*Cymodoce japonica* provisionally accept
M3_S-34.02	*Cymodoce japonica*	*Cymodoce japonica* provisionally accept
M3_S-34.03	*Cymodoce japonica*	*Cymodoce japonica* provisionally accept
M1_S-17.01	*Cypsiphimedia mala*	*Cypsiphimedia mala* provisionally accept
M3_S-29.01	*Diadumene lineata*	*Diadumene lineata* confirm
M3_S-29.02	*Diadumene lineata*	*Diadumen lineata* confirm
M3_S-29.03	*Diadumene lineata*	*Diadumen lineata* confirm
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*	*Diplsoma listerianum* confirmed
M1_M-18.03	*Diplosoma listerianum*	*Diplsoma listerianum* confirmed
M1_M-1.02	*Distaplia dubia*	*Distaplia dubia* provisionally accept; not near *Distaplia colligans* or other Clavelinidae
M1_M-1.03	*Distaplia dubia*	*Distaplia dubia* provisionally accept; not near *Distaplia colligans* or other Clavelinidae
M1_M-1.04	*Distaplia dubia*	*Distaplia dubia* provisionally accept; 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 accept
M3_S-31.02	*Eualus leptognathus*	*Eualus leptognathus* provisionally accept
M3_S-31.03	*Eualus leptognathus*	*Eualus leptognathus* provisionally accept
M1_S-40.01	*Eudendrium* sp.	Hydrozoa; distant from *Eudendrium* records, closer to *Bouganvillia*
M1_S-40.02	*Eudendrium* sp.	Hydrozoa; distant from *Eudendrium* records, closer to *Bouganvillia*
M1_S-40.03	*Eudendrium* sp.	Hydrozoa; distant from *Eudendrium* records, closer to *Bouganvillia*
M3_S-9.03	*Eulalia* sp.	Hydrozoan (epibiont?)
M3_M-32.01	*Eulalia viridis japanensis*	*Eulalila 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 accept
M3_K-22.07	*Gammaropsis japonica*	*Gammaropsis japonica* provisionally accept
M3_K-22.09	*Gammaropsis japonica*	*Gammaropsis japonica* provisionally accept
M3_S-44.02-06	*Gitanopsis* sp.	*Gitanopsis* sp. provisionally accept
M16_M-31	*Gordonodius zelleri*	Not *Gordomodius*? Seems deeply contained within Leucothoe tree.
M3_M-12.01	*Halecium pusillum*	*Halecium pusillum* provisionally accept
M3_M-12.02	*Halecium pusillum*	*Halecium pusillum* provisionally accept
M3_M-12.03	*Halecium pusillum*	*Halecium pusillum* provisionally accept
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* (same as sitiens herein)
M3_M-39.01	*Halichondria* sp.	*Halichondria* (same as sitiens herein)
M3_M-39.02	*Halichondria* sp.	*Halichondria* (same as sitiens herein)
M3_S-66.01	*Haliclona* sp.	*Haliclona* sp.
M3_S-40.01	*Halosydna brevisetosa*	*Halosydna brevistosa* of China not Canada
M3_S-40.02	*Halosydna brevisetosa*	*Halosydna brevistosa* of China not Canada
M3_S-62.01	*Harmothoe* sp.	*Harmothoe* provisionally accept
M3_S-56.01	*Hemigrapsus takanoi*	*Hemigrapsus takenoi*
M3_S-56.02	*Hemigrapsus takanoi*	*Hemigrapsus takenoi*
M3_S-56.03	*Hemigrapsus takanoi*	*Hemigrapsus takenoi*
M3_S-32.02	*Heptacarpus rectirostris*	*Heptorostris rectirostris* provisionally accepted
M3_S-32.03	*Heptacarpus rectirostris*	*Heptorostris rectirostris* provisionally accepted
M3_S-32.04	*Heptacarpus rectirostris*	*Heptorostris rectirostris* provisionally accepted
M3_M-2.01	*Hermilepidonotus helotypus*	*Halosydna brevistosa* of China not Canada
M16_M-16.1	*Hiatella orientalis*	*Botrylloides violaceus*
M16_M-16.5	*Hiatella orientalis*	*Botrylloides violaceus*
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*; contaminant
M16_MS-10.4	*Jassa marmorata*	*Jassa* sp., not *marmorata*; cf GU048162
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* provisional *cf Caprella* sp. 2 (Genbank KC146254)
M3_S-23.02	*Lepidonotus elongatus*	*Lepidonotus elongatus* provisional *cf Caprella* sp. 2 (Genbank KC146254)
M3_S-23.03	*Lepidonotus elongatus*	*Lepidonotus elongatus* provisional *cf Caprella* sp. 2 (Genbank KC146254)
M3_S-14.02	*Leucothoe nagatai*	*Leucothoe nagatai* provisionally accept
M3_S-14.03	*Leucothoe nagatai*	*Leucothoe nagatai* provisionally accept
M3_S-14.04	*Leucothoe nagatai*	*Leucothoe nagatai* provisionally accept
M3_S-57.06-08	*Liljeborgia serrata*	*Liljeborgia serrata* provisionally accept, closest Gammaridean in Genbank is *Cyclocaris*
M16_M-27	*Lirularia iridescens*	*Lirularia iridescens* confirmed

M3_K-44.01	*Maera pacifica*	*Maera pacifica* provisionally accept; closest Genbank record is *M. loveni*
M3_K-44.02	*Maera pacifica*	*Maera pacifica* provisionally accept; closest Genbank record is *M. loveni*
M3_K-44.03	*Maera pacifica*	*Maera pacifica* provisionally accept; closest Genbank record is *M. loveni*
M3_K-44.07-06	*Maera pacifica*	Maera pacifica provisionally accept; 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 accept
M3_S-48.02	*Marphysa* sp.	*Marphysa* sp. Provisionally accept
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* conflict in Genbank
M3_S-15.01	*Melita rylovae*	*Melita rylovae* provisionally accept
M3_S-15.02	*Melita rylovae*	*Melita rylovae* provisionally accept
M3_S-15.03	*Melita rylovae*	*Melita rylovae* provisionally accept
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*	*Monocorphium acherusicum* confirmed
M3_M-17.02-05	*Monocorophium acherusicum*	*Monocorphium acherusicum* confirmed
M3_S-16.02-04	*Monocorophium uenoi*	*Monocorophium ueunoi* provisionally accepted
M16_M-37	*Musculus cupreus*	*Musculus cupreus* provisionally accept
M16_MS-18	*Musculus cupreus*	*Musculus cupreus* provisionally accept
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*; contaminant?
M3_K-9.07	*Nemertellina yamaokai*	*Megabalanus rosa*; contaminant?
M3_K-9.08	*Nemertellina yamaokai*	*Megabalanus rosa*; 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*
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.	*Nicolia* sp. 1
M3_K-31.03	*Nicolea* sp.	*Nicolia* sp. 2

M16_MS-1.1	*Obelia* sp.	*Obelia* possibly *geniculata*
M16_MS-1.4	*Obelia* sp.	*Botrylloides violaceus*; contaminant?
M3_S-13.06	*Orchomene* sp.	*Orchomeme* sp. provisionally accept, closest Genbank record is *Ichnopus*
M3_S-13.07	*Orchomene* sp.	*Orchomeme* sp. provisionally accept, closest Genbank record is *Ichnopus*
M3_S-13.10	*Orchomene* sp.	*Orchomeme* sp. provisionally accept, closest Genbank record is *Ichnopus*
M16_M-33	*Pacificincola perforata*	*Pacificnicola perforata* provisionally accept
M3_S-60.01	*Paradexamine* sp.	*Paradexamine* sp. Provisionally accept
M3_S-19.01	*Paranthura japonica*	*Paranthura* provisionally accept
M3_S-19.03	*Paranthura japonica*	*Paranthura* provisionally accept
M3_S-19.04	*Paranthura japonica*	*Paranthura* provisionally accept
M3_K-23.06	*Parapleustes* sp.	*Parapleustes* sp. provisionally accept, closest Genbank record is *Parapleustes bicuspis*
M3_K-23.07	*Parapleustes* sp.	*Parapleustes* sp. provisionally accept, closest Genbank record is *Parapleustes bicuspis*
M3_K-23.09	*Parapleustes* sp.	*Parapleustes* sp. provisionally accept, 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*	Neridae; is not near other Platynereis; closest Genbank record is Nereis heterocirrata
M3_S-6.04	*Platynereis bicanaliculata*	*Neridae*; is not near other *Platynereis*; closest Genbank record is *Nereis heterocirrata*
M3_K-24.06	*Podocerus* sp.	*Podocerus* sp. provisionally accept
M3_M-21.01	*Polycheria* sp.	*Polycheria* provisionally accept
M3_S-54.01	*Procehpalothrix* sp.	*Cephalothrix simula*
M3_S-54.03	*Procehpalothrix* 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 accept
M3_S-45.07-11	*Stenothoe* sp. 1	*Stenothoe* provisionally accept
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 *conapus*, same as other *Styela* in voucher set
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 accept

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
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 accept
M3_K-18.02	*Watersipora cucullata*	*Watersipora subtorquata*, in conventional use as the widespread invasive
M3_K-18.03	*Watersipora cucullata*	*Watersipora subtorquata*, in conventional use as the widespread invasive
M3_K-18.04	*Watersipora cucullata*	*Watersipora subtorquata*, in conventional use as the widespread invasive
M16_MS-30	*Watersipora subatra*	*Watersipora subtorquata*, in conventional use as the widespread invasive
M3_M-22.01-04	*Zeuxo* sp.	*Zeuxo* sp.

THEME III – Rafting of Japanese Species

Chapter 9: Marine algae arriving on Japanese Tsunami Marine Debris[4]

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Abstract

Marine debris from the Great Tsunami of 2011 has been arriving in Oregon and Washington since June 2012. Many of the debris items have been laden with healthy and reproductive Japanese marine algae and there is a risk that these species could recruit to Pacific North American shores. Our project sampled and identified the algal species on debris using both morphological and molecular methods, and we also examined the characteristics of these species. On the 42 debris items that we sampled between June 2012 and July 2016, we identified more than 80 marine algal species and obtained DNA data on 53, mainly those species large enough to isolate for sequencing. The majority (55%) of the algal species were found on only 1-3 debris items, while only 9% occurred on more than 12 debris items.

The features of many of the Japanese tsunami marine debris (JTMD) species have potential for recruitment to habitats in the Pacific North America. More than 84% of the species were found to be fertile and actively releasing spores or gametes. A large percentage of the species were ephemeral (50%) and/or early successional (76%) forms capable of reproducing multiple times during a single year and of quickly colonizing new habitats. These life history and reproductive traits are reflected in the wide distribution of many of the species: 60% of the species are widespread, reported from multiple continents, and an additional 16% are well-known global invaders from Asia. Fifteen percent were limited to Asia, and 9% occur only on Pacific North American and Asian shores. Based on published data, 49 of the 80 JTMD algal species (61%) were already present in Pacific North America before the tsunami, with 8 of these documented to be from earlier introductions. The remaining species already present in Pacific North America and identified on debris were either native to the northeast Pacific or cryptogenic.

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[4] A version of this chapter has been submitted for publication at a peer-reviewed journal.

Introduction

Marine debris from the Great Tsunami of 2011 has been arriving on Oregon (OR) and Washington (WA) shores since 2012. The purpose of the current research was to complete a comprehensive taxonomic account of the marine algae arriving on Japanese Tsunami Marine Debris (JTMD) in Oregon and Washington and to evaluate the possibility of these species invading Pacific North American shores. Since the debris often arrived carrying a wide variety of healthy Japanese marine algae, we devised a project to monitor and characterize these species. Our project has involved: (1) Identifying and characterizing the algal species found on JTMD, including their genetic structure, and (2) Determining the percentage of JTMD species that already occur in Pacific North America so that new introductions are not confused with earlier colonization.

Methods

Identifying and characterizing the JTMD algal species

Since the 2012 landing of the Misawa 1 dock at Agate Beach, Oregon, a variety of state workers, volunteers, and scientists have helped us to collect algal samples for the project. Since the debris objects were not always found and collected when they first landed on our shores, the biota brought to us ranged from healthy samples to those in various states of decay. If the material arrived without preservative, processing began immediately since algae deteriorate 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 preserved in (1) 5% formalin/seawater (for later anatomical study and photography), and (2) silica gel (for DNA analysis).

Photo: Robin Loznak

Using the available reference literature (e.g. Yoshida 1998; Yoshida et al. 2015), preliminary morphological identifications were made in Oregon and the species traits were characterized. Since many of the species mimic one another in external appearance, the diagnostic features are most often anatomical and microscopic. Hence, for each sample, repetitive sectioning and microscopic observation was necessary to determine the species. We also scored the species for fertility, spread, longevity, successional stage, and seasonality to determine their potential to survive and spread on the Pacific coast of North America. Fertility was scored according to whether they were actively reproductive and dropping spores, spread was scored for known features relevant to the potential spread of the species, longevity was scored as either ephemeral, annual, perennial, and successional stage as either opportunistic or late successional. When possible, we also scored for the frequency and habitat of each species on the debris.

Final DNA identifications of the species were made in Kobe, Japan, via sequencing 1-3 genes 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 www.algae-base.org to determine the published global distribution of the JTMD species, including the general extent of their ranges (widespread, North Pacific, or Asian). To resolve local distributions, we used public and private herbarium databases, checklists compiled by state and national surveys, and personal collection data.

Results and Discussion

Debris landings along the Oregon and Washington coast


Photo credit: Hideaki Maki

From June 2012 to July 2016, many hundreds of debris items of assorted sizes and shapes came ashore on the Oregon and Washington coasts. Larger debris items (42 in total) carried substantial algal populations and detailed sampling and analysis was conducted in order to sample, enumerate, identify, and characterize the algal species (Appendix 9.1). These items were documented as suspected or confirmed JTMD (according to criteria detailed in Chapter 8) and each was assigned a JTMD-BF number. In addition, 28 smaller plastic debris items, too small to be definitively traced back to the tsunami were also collected and processed for our study of a new species, *Tsunamia transpacifica* (West et al. 2016; Appendix 9.2). Tabulating only the algae from BF numbered items for this study, we identified and characterized a total of 80 algal species from JTMD (Appendix 9.3), of which 31 species were not yet known to be present in Pacific North America (Appendix 9.4).

Debris types and their algal species load

The 42 BF-debris items examined for the algal project included 12 different types of debris. In order to determine the importance of each debris type in the transport of species, the algal species on each type was enumerated (Figure 9-1). The greatest number of species (29) was found on the Misawa 1 Dock, the first debris item to arrive in Oregon. Although there were only four docks or dock pieces sampled, they averaged nearly 16 algal species each, more than on any other debris type. On all four, a total of 49 species occurred. Vessels (boats) were the most common type of debris in the study (24) and averaged only 11 species per item. In total vessels carried 61 species, more than any other category of debris. The species richness on the other debris types was comparatively small.

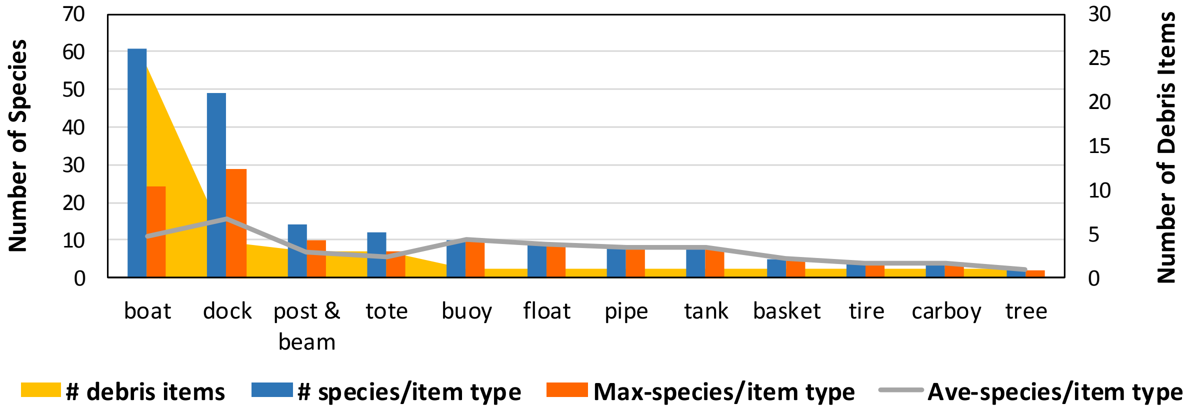

Figure 9-1. Debris types and number of algal species present.

On the 42 debris items sampled, the most widespread species were *Petalonia fascia* and *Feldmannia mitchelliae*, each found on 24 debris items. Also common were *Ectocarpus commensalis* (22), *Ulva compressa* and *Colaconema daviesii* (20), *Ulva linza* (17), and *Punctaria latifolia* (14). Only seven species occurred on more than 12 debris items. By far the majority of species (55% or 44) were limited to only 1-3 debris items.

The seasonality of the debris and its attached species

The arrival of JTMD along the Oregon and Washington coasts was somewhat seasonal (Figure 9-2). Most of the debris we obtained arrived between January and June and then very few items came ashore between July and December. Across all years, the number of debris items peaked (at 16) in March-April when ten of the 24 debris vessels and numerous other items arrived (see also Chapter 4). However, the greatest number of algae species per month (57) peaked later in May-June when eight vessels and the Misawa 1 Dock arrived.

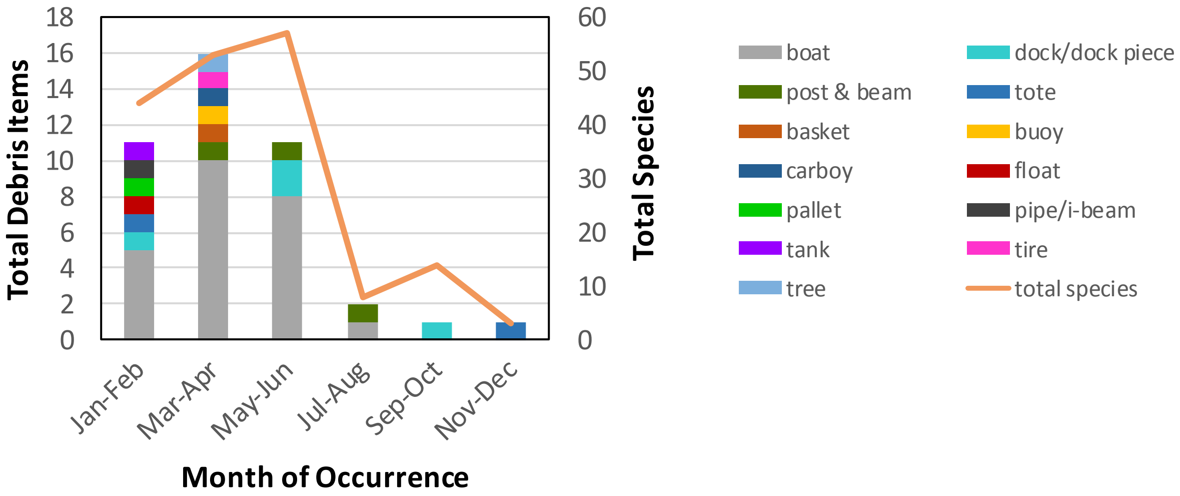

Figure 9-2. Seasonality of debris types and total species load from 2012 to 2016.

Characteristics of the debris species

A wide variety of algal species have arrived on JTMD over the course of this study. A total of 80 macroalgal species have been identified from the debris, and these consist of 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 this is not understood, but it seems likely that this ratio is not only affected by water temperature but that it can also be influenced by the unusual environmental conditions that occur around floating debris.

We characterized each of the species for features that might lead to their wider dispersal and spread after arrival. These included: their reproductive state, their longevity type (ephemeral, annual, or perennial), and their typical successional stage in the field (opportunistic early colonizers or late successional types). By far the majority of the JTMD algal species (84%) were actively reproductive when sampled (Figure 9-3b). Most were producing gametes or spores (*Ectocarpus, Undaria, Polysiphonia, Ulva*), but some of the species were instead developing asexual propagules or fragmenting (*Sphacelaria, Codium, Scytonematopsis*). The data on the longevity types (Figure 9-3c) showed that a large proportion of the species were ephemerals (50%), which are short-lived species that are capable of reproducing repeatedly and recycling themselves throughout the year whenever the conditions are appropriate. A moderate number were annuals (35%), species that last for up to 1 year, and only a few (15%) were 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 only a minor component of the debris flora, comprising only 24% of the species. The opportunistic species, well known for their ability to quickly colonize barren areas, were far more abundant, and composed 76% of the debris species.

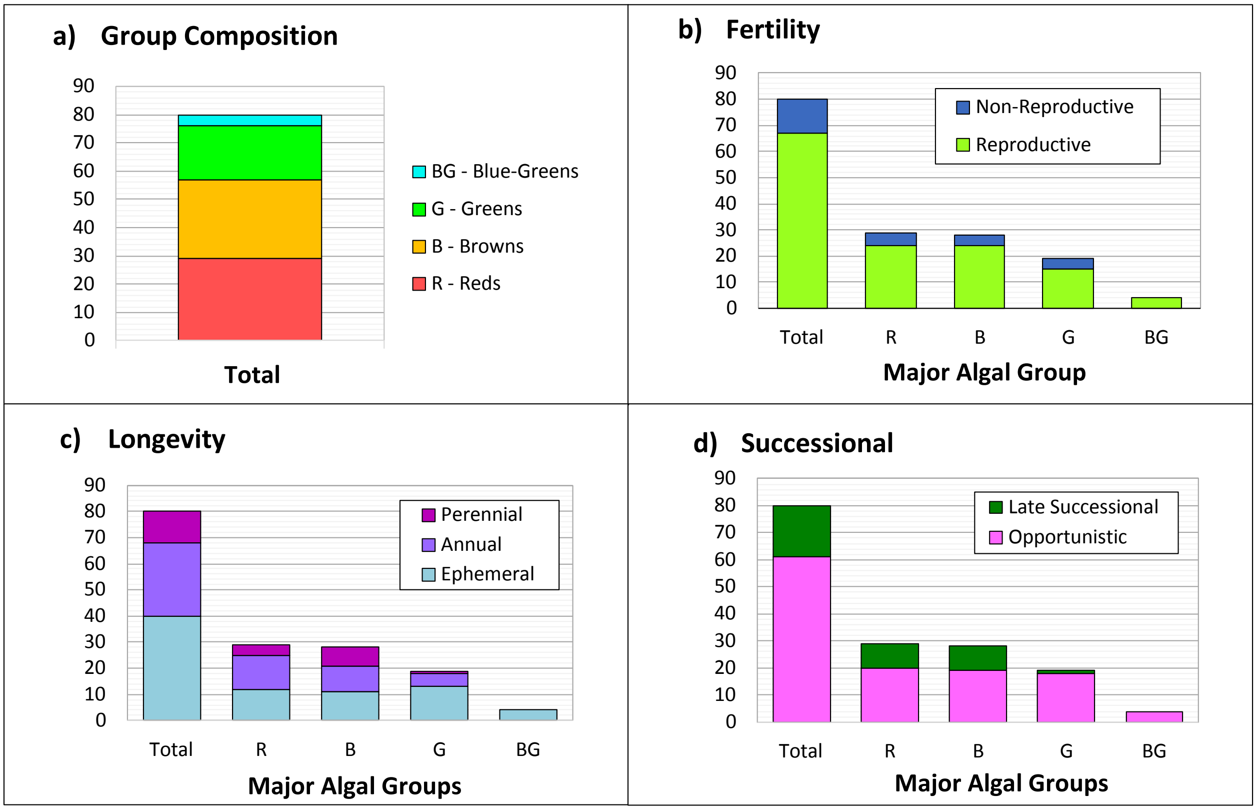

Figure 9-3. Characteristics of marine algae associated with JTMD a) group composition, b) fertility at time of sampling, c) longevity, and d) successional type.

The global occurrence of the debris species

We grouped the species into four different categories of global distribution, using the published data listed in AlgaeBase. The North Pacific (NP) category included those species that are known only from both sides of the North Pacific. There were two Asian categories: those that were limited only to Asia (A) and those Asian species that are also documented to be introduced in other areas around the world (A+). The Cryptogenic (C) category included those widespread species with unknown origins that have been reported to occur in multiple oceans.

Using these categories, the global distribution of the algal species that were found on JTMD was assessed. Sixty percent (48) of the species were cryptogenic. This category contained a large proportion of ephemeral (71%) and/or opportunistic species (92%), including all of the bluegreens and most of the green algae. These highly reproductive species often foul boats and become widespread. The North Pacific group was limited to 9% (7) of the species and the Asia only group represented 15% (12) of the species. Their limited ranges possibly relate to their methods of dispersal. The Asian+ species, which include the best known of the JTMD species, included only 16% (13) of the total JTMD species (Table 9-1). These species have been well studied and many are known invaders around the world; their global distributions have been documented through sequencing. Of the 13 Asian+ species on debris, eight are already known to occur on Pacific shores of North America. All eight are known from California, but two have also been found in Oregon and/or Washington. Many of the Asian species already resident in the Pacific North America and elsewhere around the world are thought to have been introduced with aquaculture species (Miller, Aguilar-Rosas, and Pedroche 2011). In total, 31 of the species found on JTMD were not yet found on the Pacific coast of North America.

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

Group	Name	Pacific North America Records
B	*Mutimo cylindricus*	CA
B	*Saccharina japonica*	
B	*Scytosiphon gracilis*	CA
B	*Undaria pinnatifida*	CA
G	*Codium fragile* subsp. *fragile*	CA, WA
R	*Ulva australis*	CA, OR, WA
R	*Antithamnion nipponicum*	CA
R	*Chondrus giganteus*	
R	*Grateloupia turuturu*	CA
R	*Neosiphonia japonica*	
R	*Polysiphonia morrowii*	
R	*Pyropia yezoensis*	
R	*Schizymenia dubyi*	CA

Survival and reproduction of the debris algal species

The algal species reaching Pacific shores of North America during this study survived at sea for a minimum of 15 months (Misawa 1 Dock of June 2012) and some survived for more than five years (Falcon Cove Boat of July 2016). For the surviving species, each must have had its basic requirements met during the journey; suitable substrate for attachment, appropriate submergence, adequate light and temperature, and sufficient nutrients. An unknown proportion of species did not survive the journey either a result of stresses at sea or the variable life history features of the species, or both. Some survival observations could be explained through a basic knowledge of the species. *Saccharina japonica*, the largest kelp on debris is a biennial, living only 2 years. On the Misawa 1 Dock (1 year after the tsunami), it was very abundant, the blades were 4-5 feet long, and it appeared to be 1-2 years old. By the second year (2 years after the tsunami), no large thalli were present, and only a few small blades were present, likely the first-year progeny that had seeded at sea. After that, no further plants were observed. Many of the other kelps and large algae were annuals, surviving only until our first year of observation suggesting that they did not reseed during the following years.

The most successful survivors were the ephemerals and opportunistic species. The lifespan of most of these species is relatively short, so to survive on debris, the species recycle themselves through sexual or asexual reproduction many times during each year and then recolonize the debris, often in greater abundance than before. The ephemerals and opportunistic species observed on debris were nearly always fertile and very widespread on debris. These species groups, indeed the best suited for a long survival on debris, are also the best equipped for quickly colonizing new habitats that they encounter.

The species arriving on the Pacific shores of North America were amazingly fertile. One environmental feature causing this might be the increase in nutrients as they arrived in the nearshore compared to the oligotrophic conditions at sea, but since we did not sample the items at sea this remains uncertain. Based on their survival success alone, many of the debris species did remain fertile throughout the trip, enabling them to recycle their populations. Recruitment of these species is possible if the right conditions for growth of the spores or propagules are met (primarily temperature, nutrients, light, and substratum). Sea water temperatures along the Washington, Oregon, and southern British Columbia coast (9-11.5°C; Payne et al. 2012) are within the range found along the Tōhoku coast of Japan so it is possible that they are sufficient for the survival of many of the debris species. However, one obstacle that may impede recruitment has been habitat in the receiving environment. Debris items along the OR and WA coast nearly always landed on sandy beaches where the hard substratum that is necessary for the recruitment of algal spores was not available. Since most algal spores and propagules are short-lived and cannot travel more than a few meters, this would prevent most recruitment.

Conclusions

Using both morphological and molecular methods, our study identified and characterized 80 marine algal species that were found on 42 JTMD items that landed on Oregon and Washington shores from 5 June 2012 (Misawa 1 dock, from Agate Beach, Oregon) to 26 July 2016 (the Falcon Cove boat). The debris landings occurred mainly from January through June of each year, and almost no debris could be found between July and December. Although a wide variety of debris


Photo credit: Hideaki Maki

items washed in, the greatest diversity of algal species occurred on the larger and more abundant items: four floating docks and their fragments supported a total of 49 species and 24 derelict boats carried in 61 algal species. Each item contained a diverse and often unique array of species. Only a few species were widespread*: Petalonia fascia* and *Feldmannia mitchelliae* each occurred on 24 of the 42 debris items. Most of the algal species (55%) were limited to only 1-3 debris items. The 13 species on JTMD that are Asian-origin with global introductions are the highest profile JTMD species; all have been well studied and are known to be introduced to a number of areas around the world. Detection of new algal introductions from JTMD in Pacific North America will require careful monitoring in the field and both microscopic and molecular screening of the material to confirm identity of these species.

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Appendices

Appendix 9-1. Japanese Tsunami Marine Debris items collected for the algal study

Appendix 9-2. Samples of plastic debris collected on Oregon and Washington beaches in 2015-2016 containing Stylonematophyceae crusts

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

Appendix 9-4. JTMD algal species not yet present in Pacific North America (WA, OR, CA) and their global residency

Appendix 9-1. Japanese Tsunami Marine Debris items collected for the algal study

#	BF #	State	Site Name (my 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
20	**BF-160**	OR	Tillamook Bay spit	tree	Apr 26	2014	2
21	**BF-171**	OR	Tillamook Bay spit	post & beam	Apr 25	2014	7
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

Appendix 9-2. Samples of plastic debris collected on Oregon and Washington beaches in 2015-2016 containing Stylonematophyceae crusts

GIH #	psbA Tsunamia	rbcL Sp. 2	Plastic debris object	Site	State	Collection Date	Collector
130	x		White tray fragment	Long Beach	WA	3/2/2015	Lewis
146*	x		White bottle	Long Beach	WA	11/5/2015	Lewis
422			Black buoy	Beverly Beach	OR	12/17/2015	Sarver
426			Light blue basket	Otter Crest	OR	12/20/2015	Sarver
430	x		Pink float fragment	Nye Beach	OR	12/26/2015	Sarver
431			Yellow basket	Nye Beach	OR	12/26/2015	Sarver
432		x	White box fragment	Nye Beach	OR	12/26/2015	Sarver
433	x		White tray & basket fragments	Long Beach dumpster	WA	1/9/2016	Barton
434			Black buoy	Long Beach dumpster	WA	1/9/2016	Barton
435			Black basket fragment	Long Beach dumpster	WA	1/9/2016	Barton
478			Red beer tote-Japanese writing	Leadbetter Point	WA	2/19/2016	Lewis
485			Black buoy	Leadbetter Point	WA	2/9/2016	Lewis
490			White jug-Clover Chemical	Leadbetter Point	WA	2/9/2016	Lewis
494			White float	Leadbetter Point	WA	2/9/2016	Lewis
496			White jug-Clover Chemical	Grayland Beach	WA	3/5/2016	Hansen
610		x	White float fragment	Nye Beach	OR	3/18/2016	Hansen
611			White broken basket	Nye Beach	OR	3/18/2016	Hansen
612	x	x	White tray fragment	Lost Creek N.	OR	3/18/2016	Hansen
613	x	x	White tubular fragment	Lost Creek N.	OR	3/18/2016	Hansen
614	x	x	White tray fragment	Lost Creek N.	OR	3/18/2016	Hansen
615	x	x	White tray fragment	Lost Creek N.	OR	3/18/2016	Hansen
616	x	x	Blue basket fragment	Yaquina Bay Lighthouse Beach	OR	3/26/2016	Hansen
617			White tray fragment	Yaquina Bay Lighthouse Beach	OR	3/26/2016	Hansen
618		x	Black broken grid	Yaquina Bay Lighthouse Beach	OR	3/26/2016	Hansen
619			Blue basket fragment	Otter Crest Beach	OR	3/26/2016	Hansen
620			White plastic disc	Otter Crest Beach	OR	3/26/2016	Hansen
621		x	White tray fragment	Nye Beach	OR	3/26/2016	Hansen
622		x	White jug-Nissan Chemicals	Quail Street Beach	OR	3/24/2016	Custer
623			White bucket-Miyabe writing	Quail Street Beach	OR	3/26/2016	Custer
630			White tray fragment	Hubbard Creek Beach	OR	11/25/2015	Treneman

*The type culture, JAW-4874, was taken from this collection.

Appendix 9-3. Marine algae identified from Japanese Tsunami Marine Debris arriving in Washington and Oregon from 2012 to 2016

Group	Name	Verification
B	*Alaria crassifolia in Kjellman et Petersen*	*
B	*Analipus japonicus* (Harvey) M.J. Wynne	*
B	*Costaria costata* (C. Agardh) De A. Saunders	
B	*Desmarestia japonica* H.Kawai *et al. in* Yang *et al.*	*
B	*Desmarestia viridis* (O.F. Müller) J.V. Lamouroux	
B	*Ectocarpus acutus* Setchell *et* N.L. Gardner	*
B	*Ectocarpus* cf. *penicillatus* (C. Agardh) Kjellman	**
B	*Ectocarpus commensalis* Setchell *et* N.L.Gardner *cpx.*	**
B	*Ectocarpus corticulatus* De A. Saunders	**
B	*Ectocarpus crouaniorum* Thuret in Le Jolis	*
B	*Feldmannia irregularis* (Kützing) G. Hamel	**
B	*Feldmannia mitchelliae* (Harvey) H.-S.Kim *cpx.*	*
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	**
B	*Mutimo cylindricus* (Okamura) H.Kawai et T. Kitayama	*
B	*Petalonia fascia* (O.F.Müller) Kuntze	*
B	*Petalonia zosterifolia* (Reinke) Kuntze	*
B	*Petroderma maculiforme* (Wollny) Kuckuck	*
B	*Protectocarpus speciosus* (Børgesen) Kornmann in Kuckuck	#
B	*Pseudolithoderma subextensum* (Waern) S. Lund	
B	*Punctaria latifolia* Greville	*
B	*Saccharina japonica* (Areschoug) C.E.Lane, C.Mayes, Druehl *et* G.W.Saunders	*
B	*Scytosiphon gracilis* Kogame	*
B	*Scytosiphon lomentaria* (Lyngbye) Link	*
B	*Sphacelaria rigidula* Kützing	*,#
B	*Sphacelaria solitaria* (Pringsheim) Kylin	
B	*Undaria pinnatifida* (Harvey) Suringar	*
G	*Blastophysa rhizopus* Reinke	
G	*Blidingia marginata* (J. Agardh) P.J.L. Dangeard *ex* Bliding	*
G	*Blidingia minima* var. *minima* (Nägeli *ex* Kützing) Kylin	*
G	*Bryopsis plumosa* (Hudson) C.Agardh	*

G	*Bryopsis stolonifera* W.J.Lee, S.M.Boo *et* I.K.Lee	
G	*Cladophora albida* (Nees) Kutzing	*
G	*Cladophora vagabunda* (Linnaeus) Hoek	*
G	*Codium fragile* subsp. *fragile* (Suringar) Hariot	*
G	*Epicladia* cf. *phillipsii* (Batters) R. Nielsen	
G	*Halochlorococcum moorei* (N.L. Gardner) Kornmann *et* Sahling	
G	*Ulothrix implexa* (Kützing) Kützing	
G	*Ulva australis* Areschoug	*
G	*Ulva compressa* Linnaeus	*
G	*Ulva intestinalis* Linnaeus	*
G	*Ulva lactuca* Linnaeus	*
G	*Ulva linza* Linnaeus	*
G	*Ulva prolifera* O.F.Müller	*
G	*Ulva simplex* (K.L. Vinogradova) H.S. Hayden *et al. sensu* Ogawa	**
G	*Ulvella viridis* (Reinke) R.Nielsen, C.J. O'Kelly *et* B.Wysor *in* Nielsen *et al.*	
R	*Acrochaetium microscopicum* (Nägeli *ex* Kützing) Nägeli *in* Nägeli *et* Cramer	
R	*Acrochaetium pacificum* Kylin	**
R	*Antithamnion nipponicum* Yamada *et* Inagaki	#
R	*Bangia fuscopurpurea* (Dillwyn) Lyngbye	*
R	*Ceramium cimbricum* H.E.Petersen *in* Rosenvinge	*
R	*Chondrus giganteus* Yendo	*
R	*Chondrus yendoi* Yamada *et* Mikami *in* Mikami	*
R	*Colaconema daviesii* (Dillwyn) Stegenga	*
R	*Colaconema thuretii* (Bornet) P.W.Gabrielson *in* Gabrielson *et al.*	*
R	*Erythrocladia irregularis* Rosenvinge	
R	*Erythrotrichia carnea* (Dillwyn) J. Agardh	
R	*Erythrotrichia incrassata* T. Tanaka	
R	*Grateloupia livida* (Harvey) Yamada	*
R	*Grateloupia turuturu* Yamada	*
R	*Leptofauchea leptophylla* (Segawa) M. Suzuki *et al.*	#
R	*Meiodiscus spetsbergensis* (Kjellman) G.W. Saunders *et* J. McLachlan	
R	*Neodilsea yendoana* Tokida	*
R	*Neosiphonia japonica* (Harvey) M.-S.Kim *et* I.K.Lee	
R	*Neosiphonia yendoi* (Segi) M.-S.Kim *et* I.K.Lee	#
R	*Palmaria mollis* (Setchell *et* N.L. Gardner) van der Meer *et* C.J. Bird	*
R	*Polysiphonia koreana* D. Bustamante, B.Y. Won *et* T.O. Cho	**
R	*Polysiphonia morrowii* Harvey	*
R	*Polysiphonia scopulorum* var. *villum* (J. Agardh) Hollenberg	**

R	*Porphyrostromium japonicum* (Tokida) Kikuchi *in* Kikuchi *et* Shin	
R	*Ptilota filicina* J. Agardh	*
R	*Pyropia pseudolinearis* (Ueda) N. Kikuchi, M. Miyata, M.S. Hwang *et* H.G. Choi *cpx.*	*
R	*Pyropia yezoensis* (Ueda) M.S. Hwang *et* H.G. Choi *in* Sutherland et al.	*
R	*Schizymenia dubyi* (Chauvin *ex* Duby) J. Agardh	*
R	*Tsunamia transpacifica* J. West, G. Hansen, T. Hanyuda *et* G. Zuccarello *cpx.*	*
BG	*Calothrix confervicola* C. Agardh *ex* Bornet *et* Flahault	
BG	*Chroococcus submarinus* (Hansgirg) Kovácik	
BG	*Lyngbya confervoides* C. Agardh *ex* Gomont	
BG	*Scytonematopsis crustacea* (Thuret *ex* Bornet *et* Flahault) Koválik *et* Komárek	

Note: Morphological identifications were made for all species. Verifications in addition to morphology included: * = sequencing; ** = sequencing with additional study in progress; # = identification by monographic experts.

Group designation: B = brown algae (Ochrophyta); C= green algae (Chlorphyta); BG = bluegreen bacteria (Cyanobacteria); R = red algae (Rhodophyta).

Appendix 9-4. JTMD algal species not yet present in Pacific North America (WA, OR, CA) and their global residency

Group	Name	Global
B	*Alaria crassifolia*	A
B	*Desmarestia japonica*	A
B	*Ectocarpus crouaniorum*	C
B	*Ectocarpus penicillatus*	C
B	*Kuckuckia spinosa*	C
B	*Petalonia zosterifolia*	C
B	*Protectocarpus speciosus*	C
B	*Pseudolithoderma subextensum*	C
B	*Saccharina japonica*	A+
B	*Sphacelaria solitaria*	C
G	*Blastophysa rhizopus*	C
G	*Bryopsis stolonifera*	A
G	*Epicladia phillipsii*	C
G	*Ulva simplex*	C
R	*Chondrus giganteus*	A+
R	*Chondrus yendoi*	A
R	*Erythrotrichia incrassata*	A
R	*Grateloupia livida*	A
R	*Leptofauchea leptophylla*	A
R	*Neodilsea yendoana*	A
R	*Neosiphonia japonica*	A+
R	*Neosiphonia yendoi*	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*	NP
BG	*Calothrix confervicola*	C
BG	*Chroococcus submarinus*	C
BG	*Lyngbya confervoides*	C

*Note that *Tsunamia transpacifica* cpx is known on debris in the North Pacific, but it has not yet been discovered on either coast.

THEME III – Rafting of Japanese Species

Chapter 10: Genetics of marine algae arriving on Japanese Tsunami Marine Debris and their invasion threat to the Pacific coast of North America[5]

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

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Abstract

In order to refine identifications of macroalgal associated with Japanese Tsunami Marine Debris (JTMD) we identified JTMD macroalgae based on morphology and genetic markers, and compare them with native populations in Japan and Pacific coasts of North America. Based on these analyses, we have obtained gene sequences useful for genetic taxonomy for approximately 190 specimens and have genetically identified 50 macroalgal species from JTMD. We have corrected the preliminary morphological identification of over 10 taxa (e.g., *Chondrus giganteus, Grateloupica turuturu*) by adding genetic data. Our genetic analyses indicated that most JTMD macroalgae had haplotypes identical with or very closely related to natural populations in the Tohoku region, so that they were confirmed to have 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 have indicated that they are genetically distinct and may cause genetic contamination: e.g., *Blidingia minima*, *Analipus japonicum*, *Petalonia fascia* and *Costaria costata*. Some species are already introduced to Pacific North American coasts by relatively recent anthropogenic introductions (e.g. *Mutimo cylindricus, Undaria pinnatifida* and *Grateloupia turuturu*), but have not been spread to the entire Pacific North American coast and have different haplotypes than that from JTMD specimens. Therefore, these new introductions will still pose a risk of accelerating the dispersal of these non-indigenous species by enriching the genetic diversity of the introduced populations.

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[5] A version of this chapter has been submitted to a peer-reviewed journal.

Introduction

After being carried across the North Pacific on currents from Japan, marine debris items from the Great Tsunami of 2011 have arrived on the Pacific North American coasts (Alaska, British Columbia, Washington and Oregon) and Hawaii. Many of these items appeared bearing Japanese marine algae. The macroalgal species were often healthy and reproductive, and may establish recruits in new habitats.

Photo credit: Hideaki Maki

During this project, we identified macroalgal species collected from Japanese Tsunami Marine Debris (JTMD) arriving on Washington and Oregon coasts by morphological and genetic studies. Marine macroalgae collected from JTMD were first identified based on morphology. However, there were sometimes specimen quality difficulties due to damage to the specimens during the landing of the debris, sampling, and transportation to the laboratory. In addition, definitive species level identification can be impossible because of unsuitable life history stages (juvenile or premature lacking reproductive structures) and poorly-defined morphological boundaries between related species. There is the possibility that some specimens sampled from the debris originated by settlement of propagules from native North American populations before landing of the debris.

In order to confirm the morphological identifications, and also to resolve these uncertainties, we have examined the JTMD macroalgae using selected genetic markers. For comparison, we also obtained genetic data from the Japanese and North American local (native) population of the species identified from JTMD. These genetic data were used as baseline information for distinguishing species newly introduced by JTMD from native or previously introduced species.

Methods

Specimen collection

Macroalgal specimens were obtained from available JTMD items (see Chapter 9). Marine macroalgae collected from JTMD were first identified based on morphology and samples preserved for further genetic analysis. Complementary samples of JTMD species were also obtained from natural habitats in Washington, Oregon and Japan.

Genetic identification of JTMD macroalgae

Macroalgal specimens sampled from JTMD were first identified based on morphology, then a part of each of the specimens was quickly dried, preserved in silica gel, and sent to Kobe University laboratory. Genomic DNA was extracted from fresh or silica gel-dried algal tissue of field-collected specimens and 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, WI, 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 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 PEG purification (Lis 1980), PCR products were sequenced using the CE DTCS Quick Start Kit (Beckman Coulter, Fullerton, CA, 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 ML analysis, we used RAxML GUI v.1.31 (Silvestro and Michalak 2012), conducting 10,000 Rapid Bootstrap searches followed by an a maximum likelihood (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.

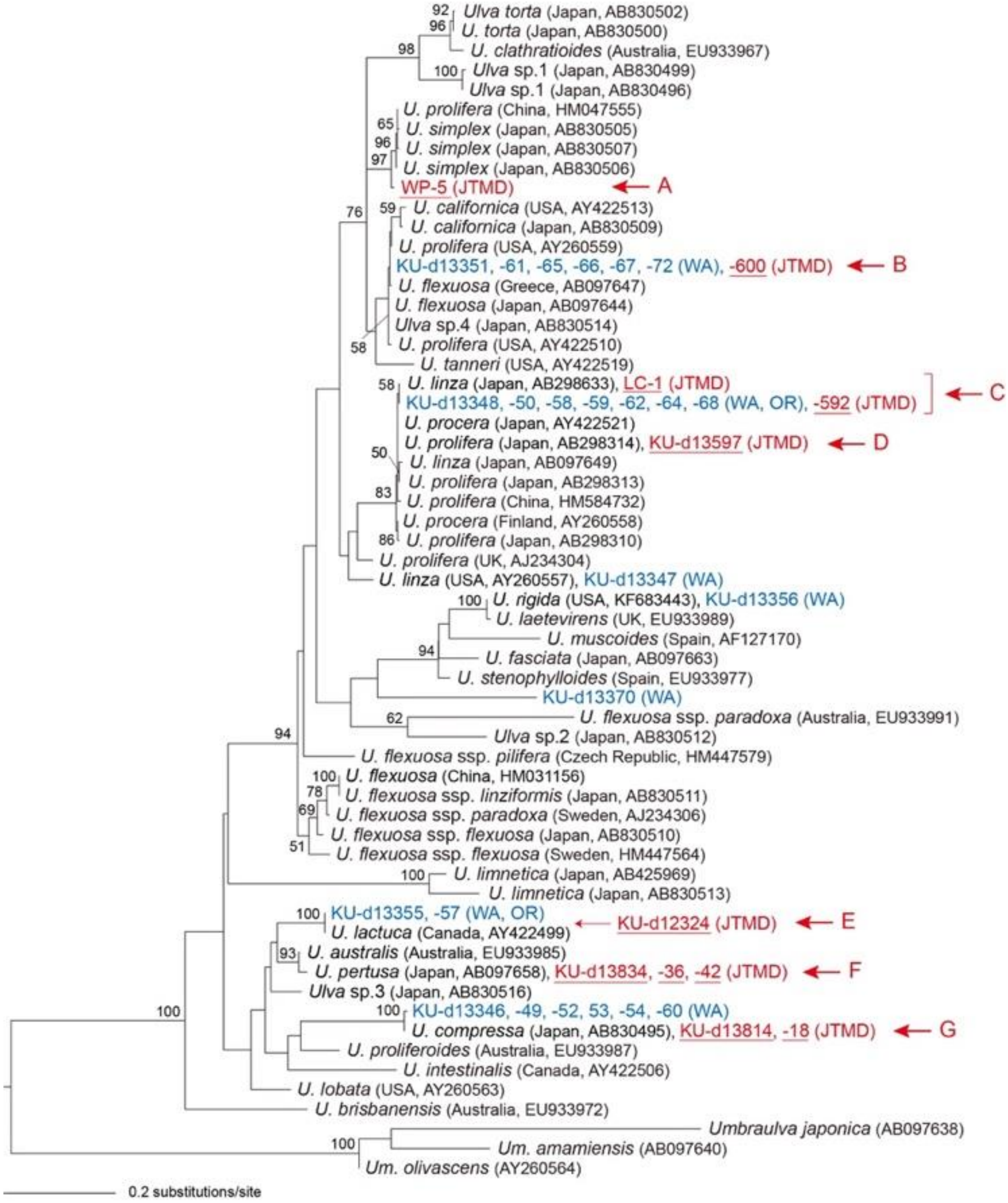
Results

Molecular phylogeny and biogeographical analyses of representative taxa

We have obtained DNA sequence data from 190 specimens collected and sent to Kobe University. The list of specimens examined for genetic analyses are presented in Appendix 10-1.

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 were included: *U. compressa, U. flexosa*?, *U. lactuca, U. linza*, *U. pertusa/australis, U. prolifera* and *U. simplex* (Figure 10-1). Among them, *U. simplex* has not been reported from Northeast Pacific coasts.



Maximum likelihood tree based on the nuclear ITS1, 5.8S rDNA, and ITS2 sequences.

Figure 10-1. Molecular phylogenetic tree of *Ulva* species based on ITS1, 5.8S and ITS2 regions of rDNA sequences (ML tree). JTMD specimens are shown in red letters, and field-collected North American specimens are shown in blue letters.

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, BC, Washington, and Oregon (Figure 10-2).

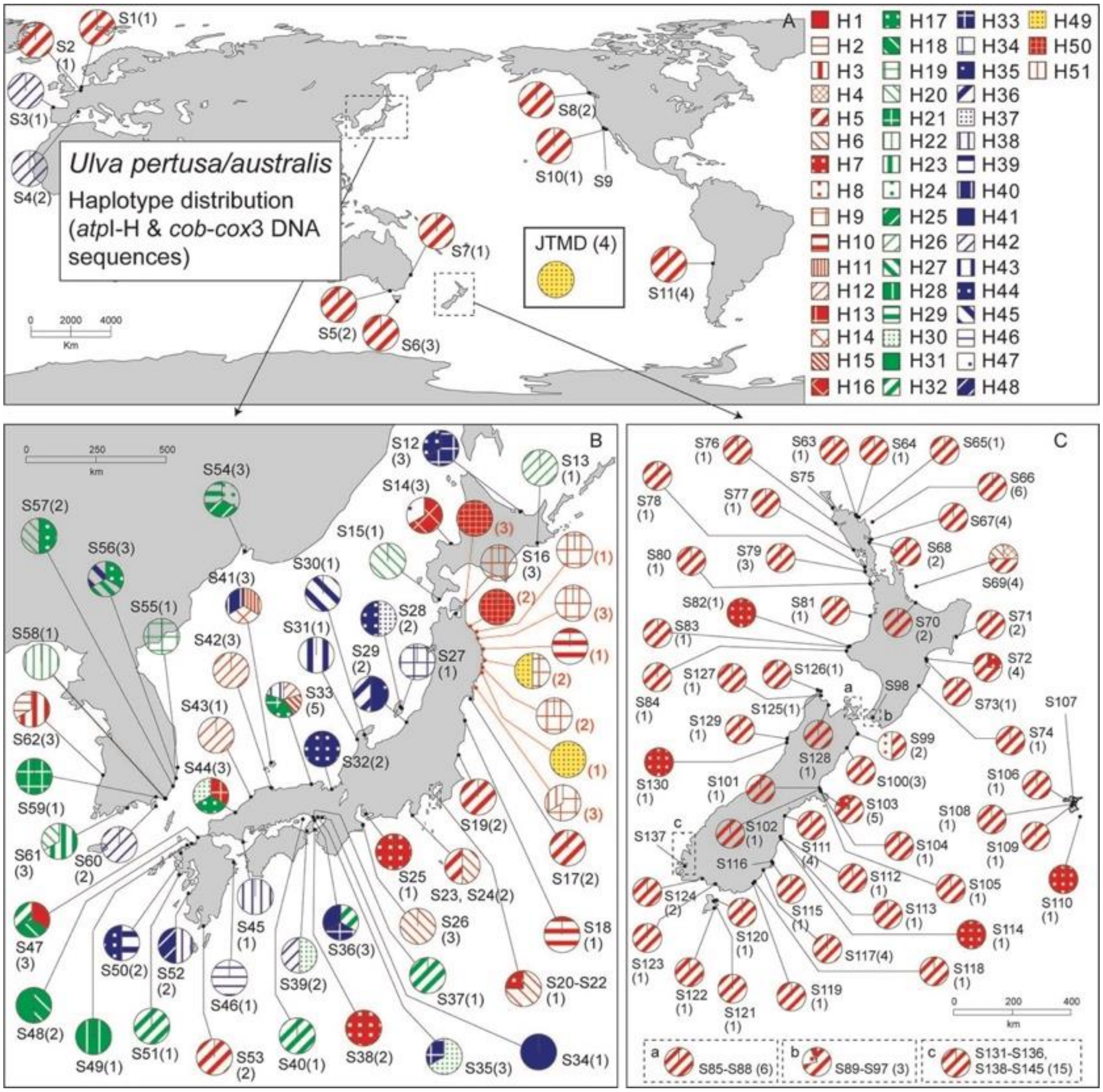


Figure 10-2. Geographical distributions of genetic types based on the ITS region sequence data of *Ulva lactuca*, and the locality of *U. lactuca* samples and the distribution of ITS genotypes.

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 determining the origin of the large JTMD items whose geographic origin was unclear, such as the derelict (unidentified) boat. We have examined the *atp*I-H and *cob-cox*3 DNA sequences of *Ulva pertusa* (=*U. australis*) specimens collected from a derelict (unidentified) boat from off-shore at Seal Rock, Oregon on 9 April, 2015, 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 (Kawai et al. *in prep*). Therefore, it is strongly suggested that the unidentified boat originated from Tohoku as JTMD.

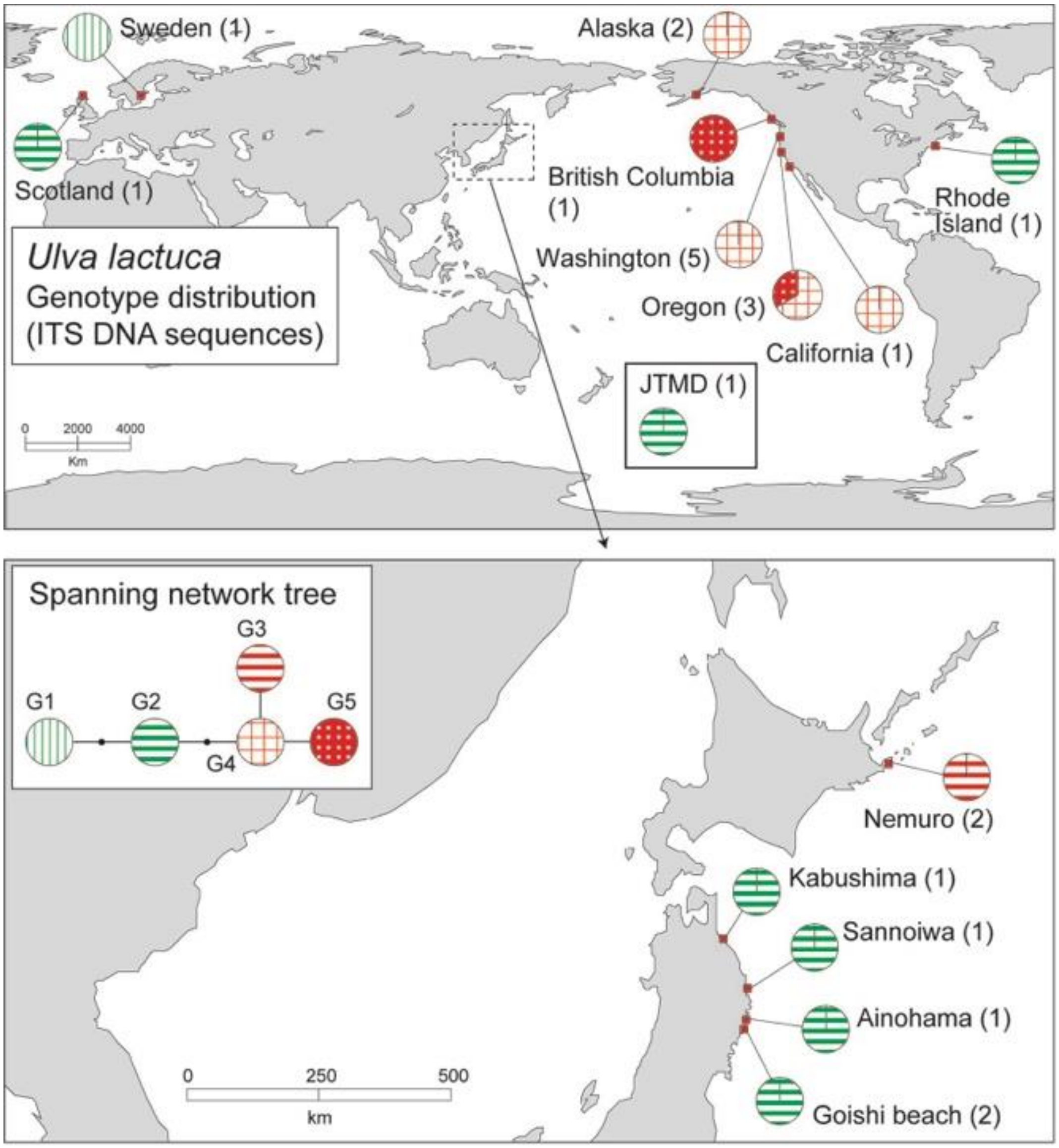
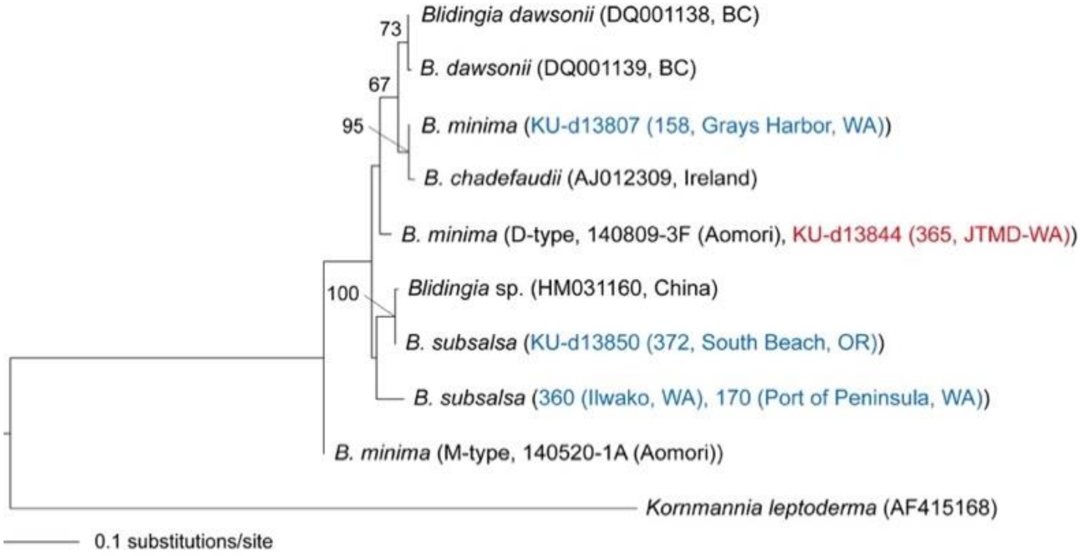


Figure 10-3. Geographical distributions of genetic types revealed from *atp*I-H and *cob-cox*3 DNA sequences.

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 in Washington (KU-d13844), confirmed that they have a sequence identical to *B. minima* collected at Aomori, Tohoku, and identified them as *B. minima* (Figure 10-4).



Maximum likelihood tree based on the nuclear ITS1, 5.8S rDNA, and ITS2 sequences.

Figure 10-4. Maximum likelihood tree of *Blidingia minima* based on the nuclear rDNA ITS region sequences (571 bp). Numbers at nodes indicate bootstrap values in maximum likelihood (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.

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

Petalonia fascia is a common 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 cold water 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 have 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 mitochondrial *cox*3 gene suggested the occurrence of two genetic groups: group-a comprised of populations in Honshu, 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, H7 were somewhat distant from H3-H6, but sometimes found mixed in Honshu, Japan (i.e. Tatehanazaki, Oiso/Suma). In contrast, the haplotypes H8-H13 were rather close. The haplotypes of the specimens on JTMD were all of group-a, whereas field-collected specimens from Washington, Oregon and California were all of group-b. Therefore, the *P. fascia* specimens were considered to have originated from Japan. Although H2 was dominant in Aomori and Iwate populations, JTMD specimens showed rather high genetic divergence (four haplotypes: H2, H4, H5 and H7). This may be explained by the lack of specimens from the southern Tohoku Area.

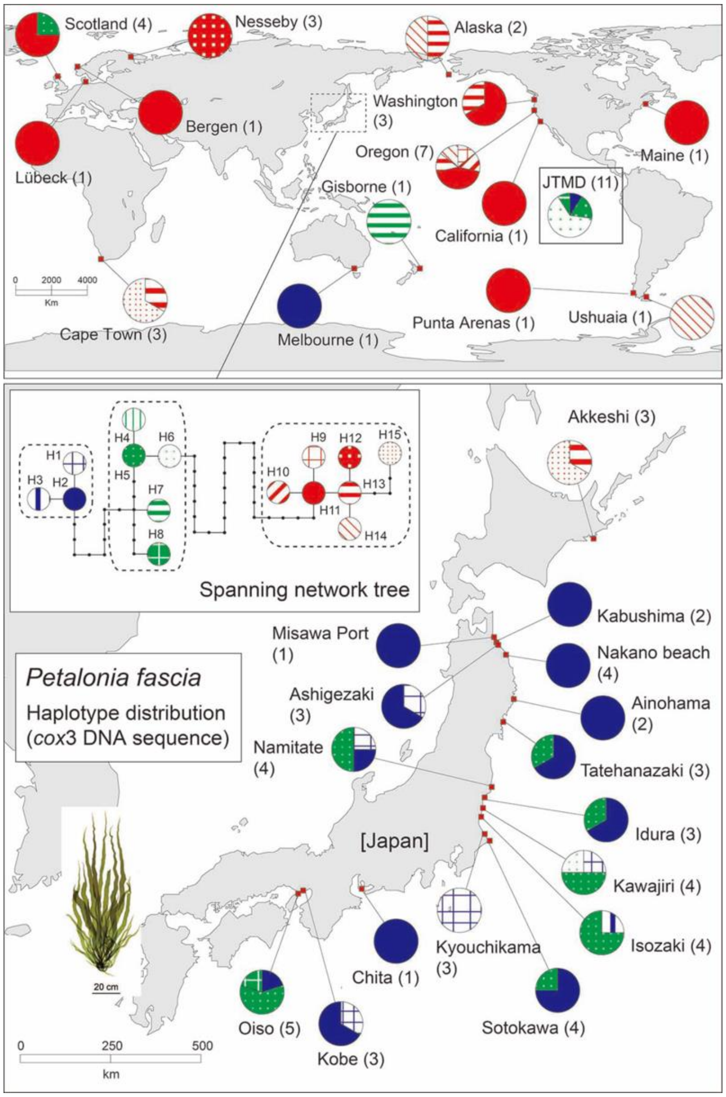


Figure 10-5. Spanning network tree based on the *cox*3 sequence data of *P.fascia*, and the locality of *P. fascia* samples and the distribution of *cox*3 haplotypes.

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

Scytosiphon lomentaria is a common 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 cold water seas. Therefore, in order to clarify the origin of the *S. lomantaria* individuals collected from JTMD, we have 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 may suggest that the intercontinental introductions of this species have frequently occurred and the original distributional pattern has been disturbed. Species level taxonomy of *Scytosiphon 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.

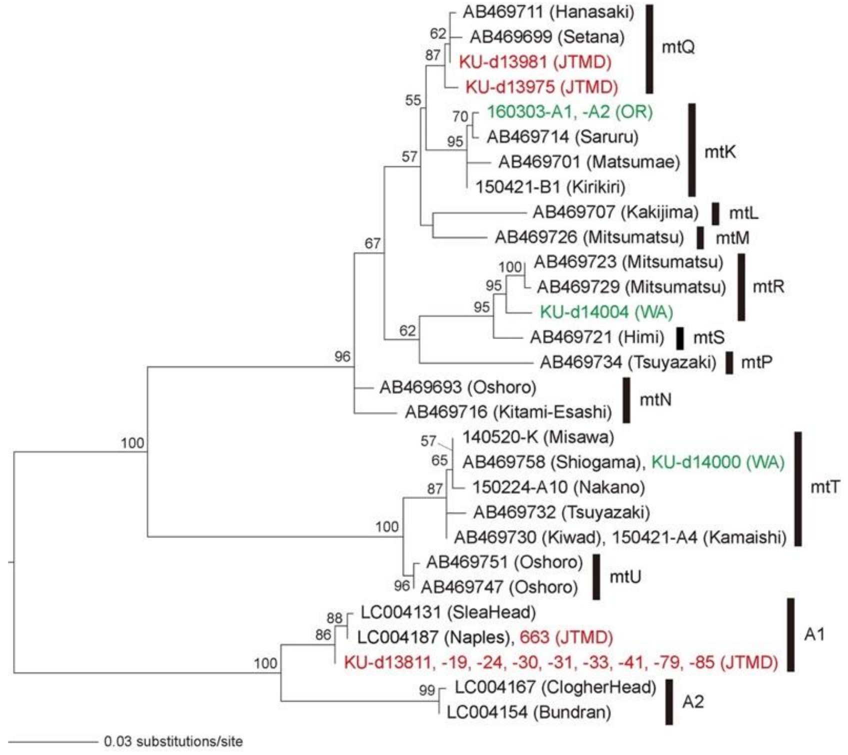
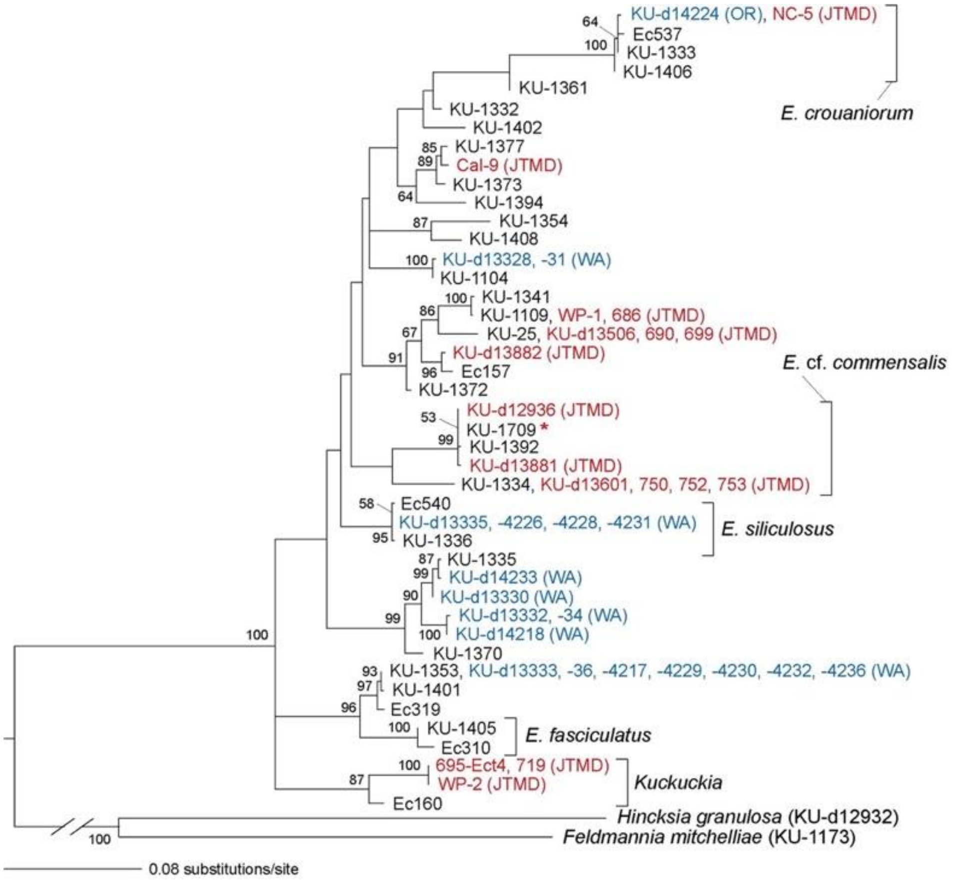


Figure 10-6. Maximum likelihood tree for *Scytosiphon lomentaria* based on the mitochondrial *cox*3 gene sequences (500 bp). Numbers at nodes indicate bootstrap values in maximum likelihood (ML) analysis. Only bootstrap values >50% are shown. JTMD specimens are shown in red letters, and field-collected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

Ectocarpus spp. (brown algae, Ectocarpales)

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 project 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 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.



*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 tree of *Ectocarpus* species based on the mitochondrial cox3 gene sequences (665 bp). Numbers at nodes indicate bootstrap values in maximum likelihood 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.

Feldmannia mitchelliae (brown algae, Ectocarpales)

Feldmannia species are filamentous brown algae resembling *Ectocarpus*, but morphologically 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 the present study, we have identified the JTMD specimens as *F. mitchelliae* by *cox*3 gene sequences (Figure 10-8). JTMD *F. mitchelliae* included several haplotypes of cox3, but unfortunately data of the genetic types of local populations in Pacific North American coasts were not available at time of publication.

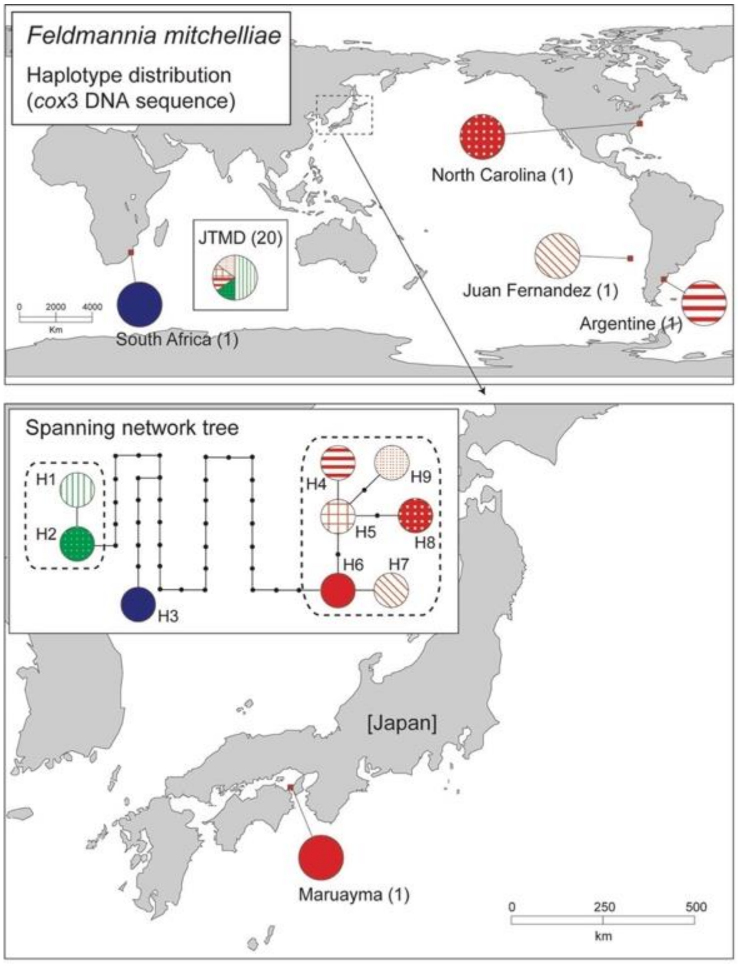


Figure 10-8. Spanning network tree based on the *cox*3 sequence data of *Feldmannia mitchelliae*, and the locality of *F. mitchelliae* samples and the distribution of *cox*3 haplotypes.

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 has 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).

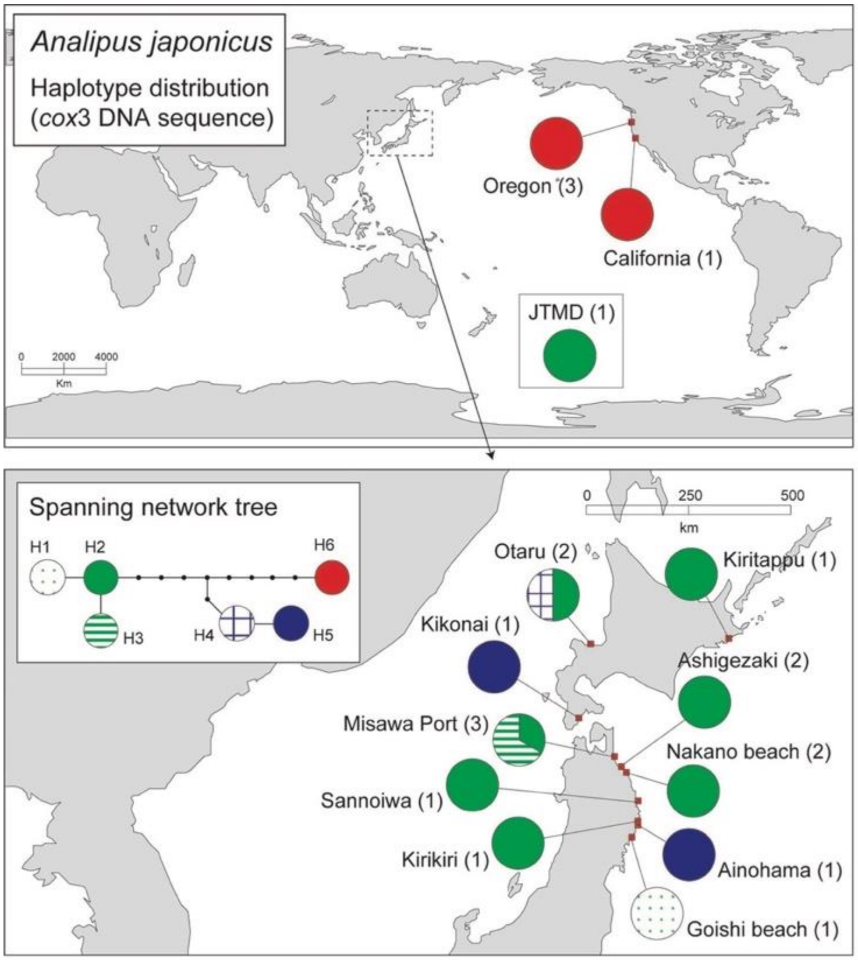


Figure 10-9. Spanning network tree based on the *cox*3 sequence data of *Analipus japonicus*, and the locality of *Analipus japonicus* samples and the distribution of *cox*3 haplotypes.

Mutimo cylindricus (brown algae, Tilopteridales)

Mutimo cylindricus is an annual brown alga originally distributed in Far-east Asia. It was shown to be introduced to Santa Catalina Island, California (Kogishi et al. 2010 as *Cutleria cylindrica* later transferred to genus *Mutimo* 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.

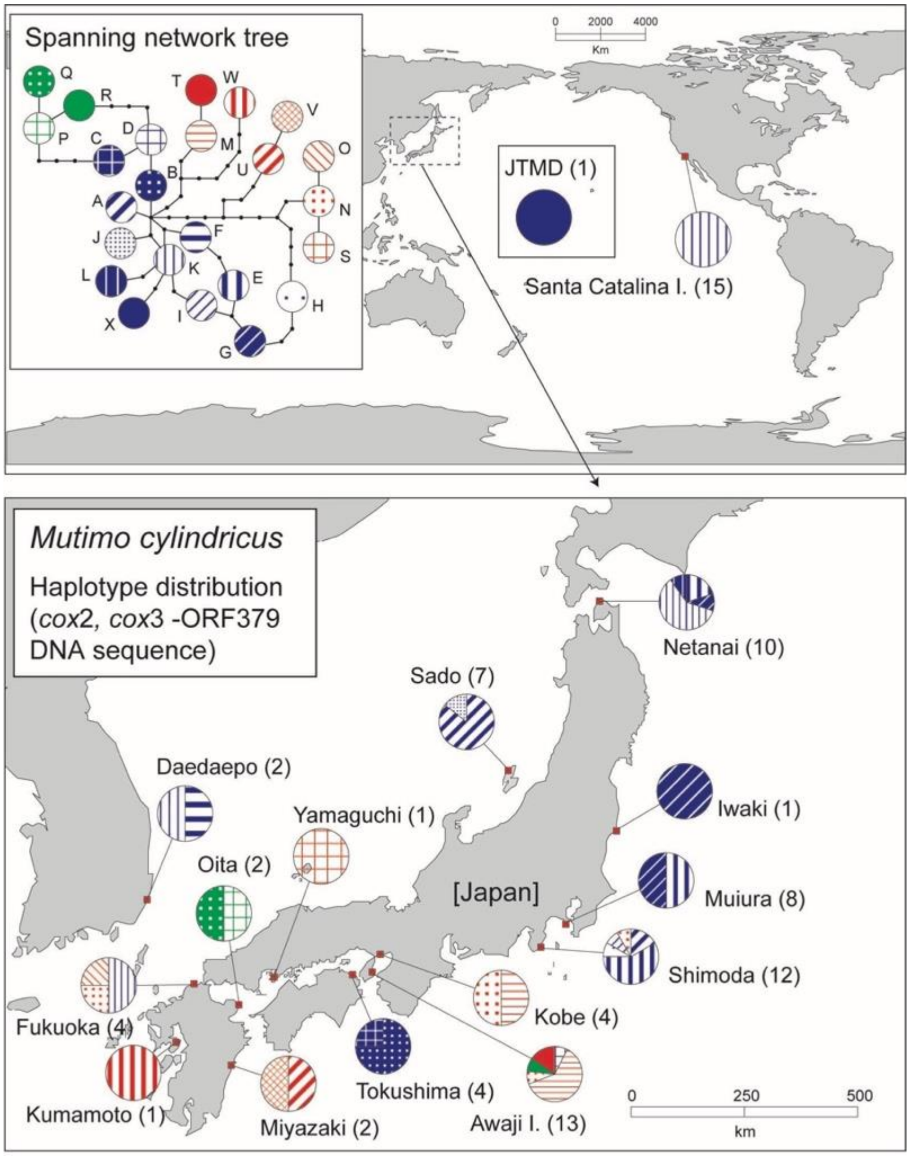


Figure 10-10. Spanning network tree based on the *cox*2 and *cox*3-ORF379 sequence data of *Mutimo cylindricus*, and the locality of *M. cylindricus* samples and the distribution of haplotypes.

Costaria costata (brown algae, Laminariales)

Costaria costata is an annual kelp species, and 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 has revealed that North American and Japanese populations are genetically distinct, although they are relatively closely related (Figure 10-11).

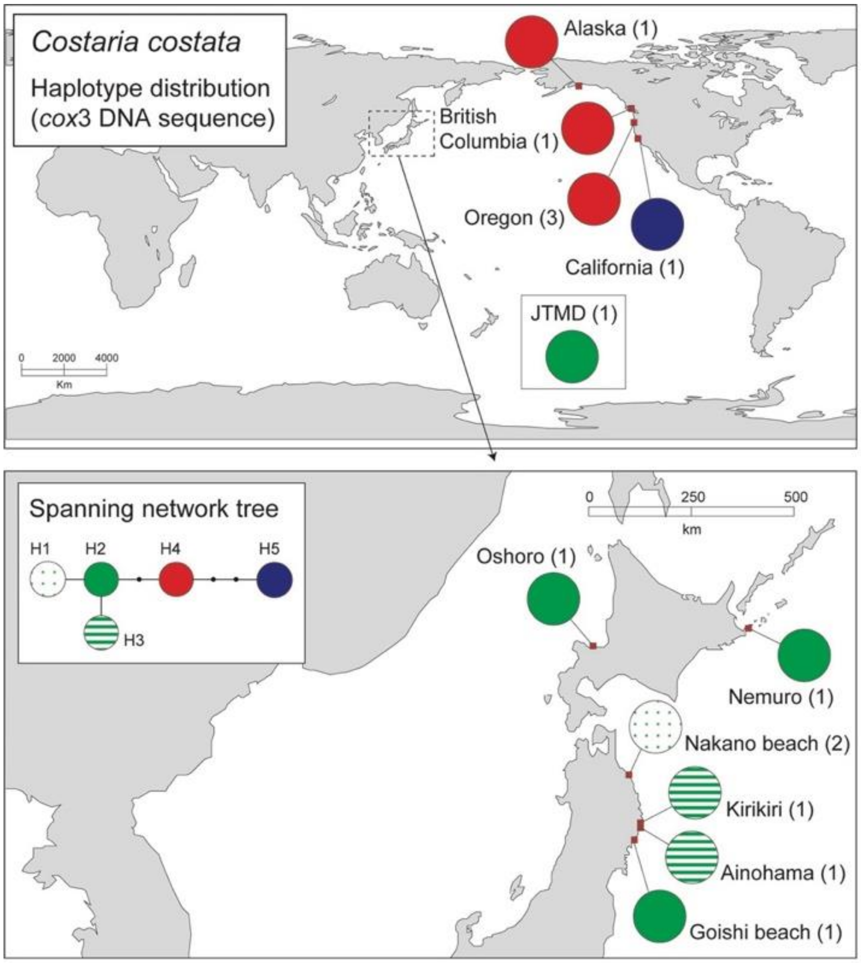


Figure 10-11. Spanning network tree based on the cox3 sequence data of *Costaria costata*, and the locality of *Costaria costata* samples and the distribution of *cox*3 haplotypes.

Saccharina japonica (brown algae, Laminariales)

Saccharina japonica is a biannual kelp species exceeding several meters in length, and constitutes one of the most important ecological elements in colder seas. *S. japonica* was found on the Misawa floating dock landing in Oregon. The species is distributed in cold water regions of the Pacific Northwest, USA, and in Tohoku and Hokkaido, Japan (Figure 10-12). The species is not distributed widely 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 the local ecosystems.

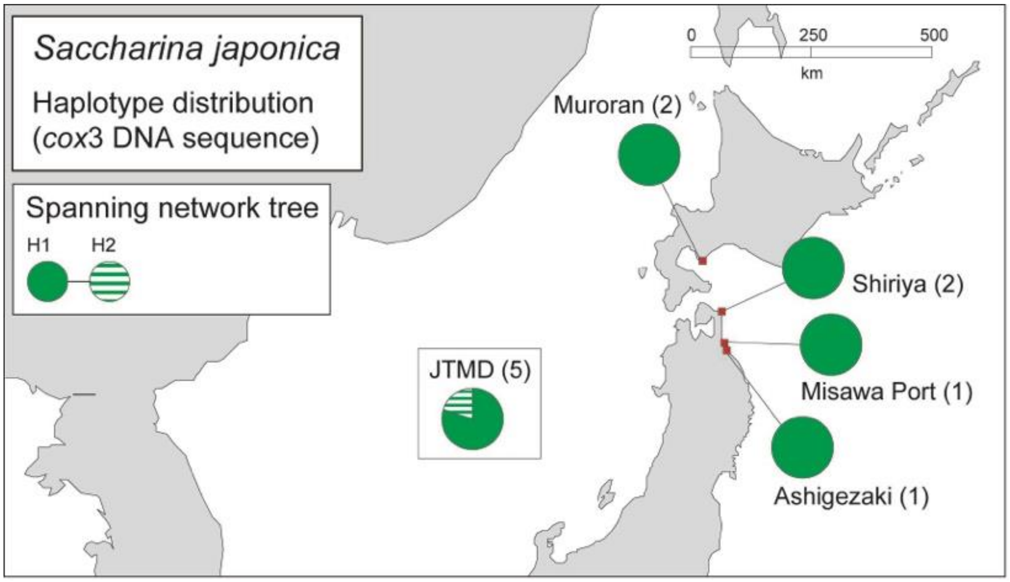


Figure 10-12. Spanning network tree based on the *cox*3 sequence data of *Saccharina japonica*, and the locality of *S. japonica* samples and the distribution of *cox*3 haplotypes.

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 Far-east Asia (Northwest Pacific), but has been introduced and has established widely both in the Northern and Southern Hemispheres (Figure 10-13). On Pacific coasts of North America, the species has been introduced to California and Pacific Mexico, but 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.

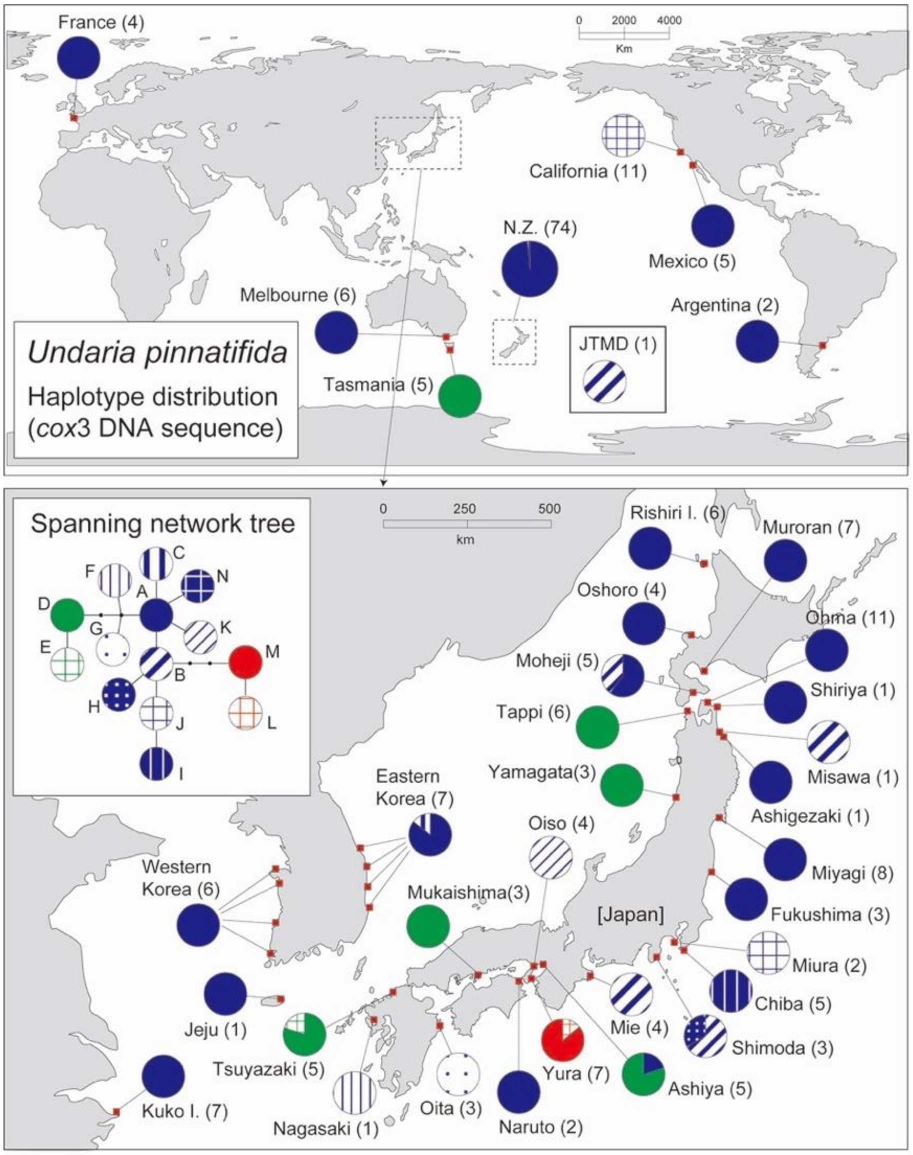


Figure 10-13. Spanning network tree based on the *cox*3 sequence data of *Undaria pinnatifida*, and the locality of *U. pinnatifida* samples and the distribution of haplotypes.

Grateloupia turuturu (red algae, Halymeniales)

Grateloupia turuturu is an annual red alga with branched membranous thalli. The original distributional range of this species is Far-east Asia, but it has been introduced to various areas in Europe, and Pacific and Atlantic coasts of North America. On Pacific coasts of North America it has been reported from California and Baja California, but has not been reported from Oregon previously. Based on the *rbcL* DNA sequence, the specimen collected from JTMD had the same haplotype as that reported from Baja California (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 some gene region with a faster mutation rate in order to distinguish the JTMD specimen from existing California/Baja California populations.

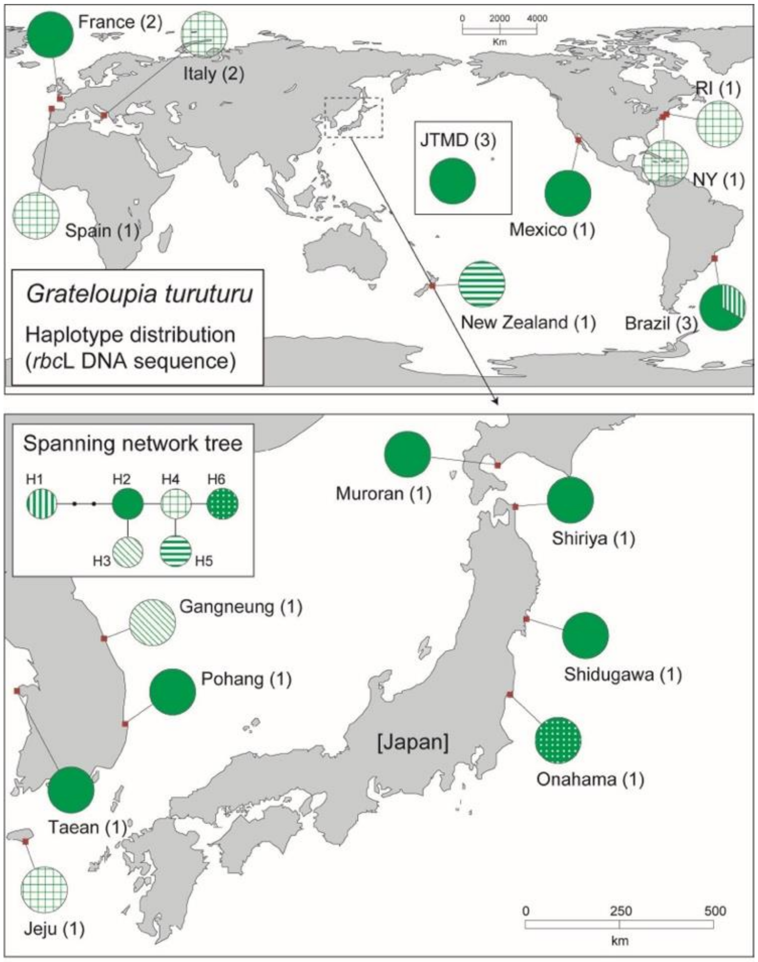


Figure 10-14. Spanning network tree based on the *rbc*L sequence data of *Grateloupia turuturu*, and the locality of *G. turuturu* samples and the distribution of *rbc*L haplotypes.

Palmaria palmata/mollis (red alga, Palmariales)

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 remains taxonomic problems in the species-level taxonomy. *Palmaria palmata* (auct. japon.) can be conspecific to *Palmaria mollis* distributed in Pacific North America, and considered to constitute an important ecological element by their relatively large size and abundance. In 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, and were genetically rather distant by about 20 bp in *cox*1 sequences from a native (local) population 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 mollis* is used for food (as 'dulse' and sold commercially, although the amount is not great in North America, but widely consumed in Northern Europe) on Pacific coasts of North America, so that its introduction could cause economic damage in addition to the risks of disturbance to the local ecosystems.

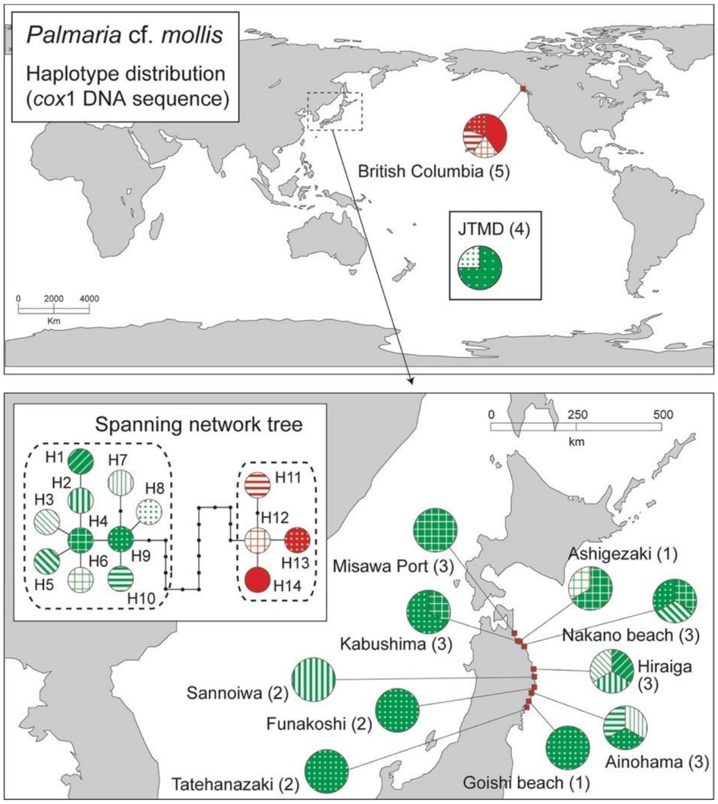


Figure 10-15. Spanning network tree based on the *cox*1 sequence data of *Palmaria palmata/P. mollis*, and the locality of *Palmaria palmata/P. mollis* samples and the distribution of *cox*3 haplotypes.

Discussion

Because of great morphological plasticity and rather limited morphological features, species level taxonomy of macroalgae, especially those of small species, is often difficult. In addition to such taxonomic difficulty, there are additional factors that made the precise taxonomy (species level identification) of JTMD macroalgal species difficult. In most cases the sampling of the JTMD specimens was done by non-specialists in algal taxonomy, and the specimens were not properly prepared for taxonomic examination. Furthermore, the sampled specimens often deteriorated before they arrived at the laboratory. Therefore, in order to compensate for these problems and improve the accuracy of identifications, we have applied genetic analyses using selected genetic markers. Based on these analyses, we have obtained gene sequences useful for genetic taxonomy for approximately 190 specimens and have genetically identified 50 species from JTMD macroalgae. We have corrected the preliminary morphological identification of over 10 taxa (e.g., *Chondrus giganteus, Grateloupica turuturu*) by adding genetic data.

Photo credit: Hideaki Maki

Genetic data were also used to confirm that macroalgal species sampled from JTMD originated from Japan, and not by secondary attachment of local macroalgae on the Pacific coasts of North America after arriving on the coasts and before their landing. 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 that this examination was important. In addition, some JTMD species are known to be distributed on both sides of the Pacific by natural distribution or by anthropogenic introductions before the Great 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 indicated that most JTMD macroalgae had haplotypes identical with or very closely related to natural populations in the Tohoku region, so that they were confirmed to have originated from Japan, and not from secondary settlement. 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 Pacific 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 japonicum*, *Petalonia fascia* and *Costaria costata*. Some species are already introduced to Pacific coasts of North America by relatively recent anthropogenic introductions (e.g. *Mutimo cylindricus, Undaria pinnatifida* and *Grateloupia turuturu*), but have not been spread to the coasts of Oregon, and had different haplotypes. Therefore, these new introductions will still pose a 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 the 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 from JTMD suggest that their natural distributional pattern may be considerably disturbed by anthropogenic activities.

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Appendices

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 KU dry specimens	Morphological identification	Genetic identification
6-Jun-12	Oregon Floating Dock	JTMD	#3	KU-d12315	*Neodilsea yendoana?*	*Neodilsea yendoana*
6-Jun-12	Oregon Floating Dock	JTMD	#4	KU-d12316	*Porphyra* sp.	*Pyropia yezoensis*
6-Jun-12	Oregon Floating Dock	JTMD	#5A	KU-d12317	*Desmarestia ligulata*	*Desmarestia japonica*
6-Jun-12	Oregon Floating Dock	JTMD	#6a	KU-d12319	*Saccharina*	*Saccharina japonica*
6-Jun-12	Oregon Floating Dock	JTMD	#6b	KU-d12320	*Saccharina*	*Saccharina japonica*
6-Jun-12	Oregon Floating Dock	JTMD	#7	KU-d12321	*Saccharina* cf. *japonica*	*Saccharina japonica*
6-Jun-12	Oregon Floating Dock	JTMD	#8	KU-d12322	*Saccharina*	*Saccharina japonica*
6-Jun-12	Oregon Floating Dock	JTMD	#9	KU-d12323	*Saccharina*	*Saccharina japonica*
6-Jun-12	Oregon Floating Dock	JTMD	#10	KU-d12324	*Ulva* cf. *japonica*	*Ulva lactuca*
Dec-12	Washington State debris boat	JTMD	WA #1	KU-d12356	*Saccharina* sp.	*Saccharina japonica*
Dec-12	Washington State debris boat	JTMD	WA #2	KU-d12357	*Ulva* sp.	*Ulva pertusa/australis*
Dec-12	Washington State debris boat	JTMD	WA #3a	KU-d12358	*Grateloupia* cf. *chaingii*	*Chondrus giganteus*
Dec-12	Washington State debris boat	JTMD	WA #3b	KU-d12359	*Polyopes? lancifolius?*	*Grateloupia turuturu*
Dec-12	Washington State debris boat	JTMD	WA #4	KU-d12360	*Cladophora* sp.	*Cladophora albida*
Dec-12	Washington State debris boat	JTMD	WA #5	KU-d12361	*Grateloupia* cf. *setchellii*	*Grateloupia livida*
29-Jan-13	Seaview Rusty Pipe	JTMD	2	KU-d12822	*Palmaria* cf. *mollis*	*Palmaria* cf. *mollis*
14-Mar-13	Ponsler Boat	JTMD	3	KU-d12823	*Punctaria* cf. *latifolia*	*Punctaria latifolia*
22-Mar-13	Jockey Cap boat	JTMD	4	KU-d12824	*Punctaria* sp.	*Petalonia fascia*
21-Feb-13	Horsefall Beach boat	JTMD	5	KU-d12825	*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
22-Mar-13	Jockey Cap boat	JTMD	6	KU-d12826	*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
5-Jan-13	Mosquito Creek dock	JTMD	8	KU-d12828	*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
29-Jan-13	Seaview Rusty Pipe	JTMD	10	KU-d12830	*Petalonia fascia*	*Petalonia fascia*
6-Feb-13	Glenden Beach boat	JTMD	11	KU-d12831	*Petalonia fascia*	*Petalonia fascia*
14-Mar-13	Ponsler Boat	JTMD	12	KU-d12832	*Petalonia fascia*	*Petalonia fascia*
21-Feb-13	Horsefall Beach boat	JTMD	15	KU-d12835	*Petalonia zosterifolia*	*Petalonia zosterifolia*
5-Jan-13	Mosquito Creek dock	JTMD	17	KU-d12837	*Ceramium cimbricum*	*Ceramium cimbricum*

2-Jan-13	HMSC outfall	JTMD?	21	KU-d12841	*Chaetomorpha linum crassa*	*Chaetomorpha linum*
29-Jan-13	Seaview Rusty Pipe	JTMD	Cal-3		*Palmaria* cf. *mollis*	*Palmaria* cf. *mollis*
5-Jan-13	Mosquito Creek dock	JTMD	Cal-4		*Codium fragile fragile*	*Codium fragile*
21-Feb-13	Horsefall Beach boat	JTMD	Cal-5		*Polysiphonia abscissa*	*Polysiphonia morrowii*
21-Feb-13	Horsefall Beach boat	JTMD	Cal-7		*Petalonia zosterifolia*	*Petalonia zosterifolia*
29-Jan-13	Seaview Rusty Pipe	JTMD	Cal-8		*Alaria (nana-form)*	*Alaria crassifolia*
29-Jan-13	Seaview Rusty Pipe	JTMD	Cal-9		*Ectocarpus fasciculatus?*	*Ectocarpus* sp.
5-Jan-13	Mosquito Creek dock	JTMD	Cal-11		*Scytosiphon gracilis*	*Scytosiphon gracilis*
5-Jan-13	Mosquito Creek dock	JTMD	Cal-14		*Bryopsis pennata*	*Bryopsis* cf. *plumosa*
6-Jan-13	Gleneden Beach boat	JTMD	Cal-15		*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
29-Jan-13	Seaview Rusty Pipe	JTMD	Cal-16		*Alaria (nana-form)*	*Alaria crassifolia*
1-Mar-13	Long Beach tire 4	JTMD	Cal-17		*Palmaria palmata*	*Palmaria* cf. *mollis*
1-Mar-13	Long Beach tire 4	JTMD	Cal-18		*Chondrus* sp.	*Chondrus yendoi*
12-May-14	Waldport Panga	JTMD	WP-1	KU-d13965	*Ectocarpus* sp.	*Ectocarpus* sp.
13-May-14	Waldport Panga	JTMD	WP-2	KU-d13966	*Ectocarpus* sp.	*Kuckuckia spinosa*
14-May-14	Waldport Panga	JTMD	WP-3	KU-d13967	*Sphacelariales*	*Sphacelaria* sp.
15-May-14	Waldport Panga	JTMD	WP-4	KU-d13968	*Petalonia*	*Petalonia fascia*
16-May-14	Waldport Panga	JTMD	WP-5	KU-d13969	*Ulva procera/prolifera*	*Ulva simplex*
29-Apr-14	Lost Creek black float	JTMD	LC-1	KU-d13970	*Ulva procera/prolifera*	*Ulva* cf. *linza*
29-Apr-14	Lost Creek black float	JTMD	LC-2	KU-d13971	*Petalonia zosterifolia/ Scytosiphon gracilis*	*Petalonia zosterifolia*
29-Apr-14	Lost Creek black float	JTMD	LC-3	KU-d13972	*Punctaria*	*Punctaria latifolia*
29-Apr-14	Lost Creek black float	JTMD	LC-4	KU-d13973	*Punctaria*	*Petalonia fascia*
26-Apr-14	Tillamook Wood	JTMD	TW-1	KU-d13974	*Polysiphonia morrowii?*	*Polysiphonia morrowii*
19-May-14	North Cove	JTMD	NC-1	KU-d13975	*Scytosiphon* sp.	*Scytosiphon lomentaria*
19-May-14	North Cove	JTMD	NC-2	KU-d13976	*Punctaria*	*Punctaria latifolia*
19-May-14	North Cove	JTMD	NC-3	KU-d13977	*Sphacelariales*	*Sphacelaria* sp.
19-May-14	North Cove	JTMD	NC-4	KU-d13978	*Ulva procera/prolifera*	*Ulva compressa*
19-May-14	North Cove	JTMD	NC-5	KU-d13979	*Ectocarpus* sp.	*Ectocarpus crouaniorum*
	(yet to be determined but JTMD)	JTMD	S-293	KU-d13981	*Scytosiphon? lomentaria*	*Scytosiphon lomentaria*
8-Sep-14	Brighton Marina	OR	66	KU-d13325	*Petalonia fascia*	*Petalonia fascia*
8-Sep-14	Jetty Fishery	OR	69	KU-d13326	*Petalonia fascia*	*Petalonia fascia*
12-Aug-14	GH Jetty Channel	WA	107	KU-d13327	*Petalonia fascia*	*Petalonia fascia*

8-Sep-14	Stackpole walk-out, Willapa Bay	WA	7	KU-d13328	*Ectocarpus* sp.	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	13	KU-d13329	*Ectocarpus* sp.	*Ectocarpus* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	20	KU-d13330	*Ectocarpus*	*Ectocarpus* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	21	KU-d13331	*Ectocarpus*	*Ectocarpus* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	35	KU-d13332	*Ectocarpus*	*Ectocarpus* sp.
8-Sep-14	Grays Harbor SW	WA	41	KU-d13333	*Ectocarpus*	*Ectocarpus* sp.
8-Sep-14	Grays Harbor SW	WA	42	KU-d13334	*Ectocarpus*	*Ectocarpus* sp.
8-Sep-14	Grays Harbor SW	WA	43	KU-d13335	*Ectocarpus*	*Ectocarpus siliculosus*
12-Aug-14	GH, Brady's Oyster	WA	60	KU-d13336	*Ectocarpus* cf. *siliculosus*	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	11	KU-d13337	*Cladophora albida*	*Cladophora vagabunda*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	12	KU-d13338	*Cladophora sericea*	*Cladophora oligocladoidea*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	14	KU-d13339	*Cladophora albida*	*Cladophora vagabunda*
8-Sep-14	Ilwaco docks	WA	82	KU-d13340	*Cladophora* cf. *microcladioides*	*Cladophora glomerata*
8-Sep-14	Grays Harbor SW	WA	36	KU-d13341	*Blidingia minima*	*Blidingia* sp.
8-Sep-14	Grays Harbor SW	WA	37	KU-d13342	*Gayralia oxyspermum ?*	*Gayralia oxysperma*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	24	KU-d13343	*Bryopsis hypnoides*	*Bryopsis* cf. *plumosa*
8-Sep-14	SW Shore	WA	47	KU-d13344	*Bryopsis hypnoides*	*Bryopsis* cf. *plumosa*
8-Sep-14	S-Bay Oyster	WA	48	KU-d13345	*Bryopsis plumosa*	*Bryopsis* cf. *plumosa*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	19	KU-d13346	*Ulva linza*	*Ulva compressa*
8-Sep-14	S-Bay Oyster	WA	49	KU-d13347	*Ulva linza*	*Ulva* cf. *linza*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	27	KU-d13348	*Ulva linza*	*Ulva* cf. *linza*
8-Sep-14	Grays Harbor SW	WA	39	KU-d13349	*Ulva linza*	*Ulva compressa*
12-Aug-14	GH Jetty South	WA	93	KU-d13350	*Ulva*	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	5	KU-d13351	*Ulva compressa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	18	KU-d13352	*Ulva compressa*	*Ulva compressa*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	26	KU-d13353	*Ulva compressa?*	*Ulva compressa*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	23	KU-d13354	*Ulva*	*Ulva compressa*
12-Aug-14	Brady's Oyster Farm	WA	58	KU-d13355	*Ulva* cf. *lobata*	*Ulva lactuca*
12-Aug-14	Brady's Oyster Farm	WA	59	KU-d13356	*Ulva* cf. *lactuca*	*Ulva rigida/laetevirens*
8-Sep-14	Brighton Marina	OR	65	KU-d13357	*Ulva lobata?*	*Ulva lactuca*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	15	KU-d13358	*Ulva prolifera*	*Ulva* cf. *linza*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	25	KU-d13359	*Ulva prolifera*	*Ulva* cf. *linza*

8-Sep-14	Grays Harbor SW	WA	38	KU-d13360	*Ulva prolifera*	*Ulva compressa*
8-Sep-14	Grays Harbor SW	WA	44	KU-d13361	*Ulva prolifera?*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	1	KU-d13362	*Ulva flexuosa*	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	10	KU-d13364	*Ulva flexuosa paradoxa?*	*Ulva* cf. *linza*
7-Sep-14	Stony Point Sands, Willapa Bay	WA	29	KU-d13365	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
7-Sep-14	Stony Point Sands, Willapa Bay	WA	30	KU-d13366	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
7-Sep-14	Stony Point Sands, Willapa Bay	WA	31	KU-d13367	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
8-Sep-14	S-Bay Oyster Farm	WA	50	KU-d13368	*Ulva flexuosa*	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	16	KU-d13369	*Ulva flexuosa*	*Ulva* cf. *linza*
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	17	KU-d13370	*Ulva flexuosa*	*Ulva* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	22	KU-d13371	*Ulva flexuosa paradoxa*	*Ulva* sp.
7-Sep-14	Stony Point Sands, Willapa Bay	WA	28	KU-d13372	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
4-Jan-14	Long Beach	JTMD	108	KU-d13501	*Ectocarpus* sp.	*Ectocarpus* sp.
4-Jan-15	Long Beach	JTMD	109	KU-d13502	*Ulva simplex*	*Ulva compressa*
20-Jan-15	Beverly Beach	JTMD	110	KU-d13503	*Punctaria* sp.	*Punctaria latifolia*
20-Jan-15	Beverly Beach	JTMD	111	KU-d13504	*Scytosiphon gracilis?*	*Scytosiphon* sp.
20-Jan-15	Beverly Beach	JTMD	112	KU-d13505	*Scytosiphon gracilis?*	*Petalonia zosterifolia*
20-Jan-15	Beverly Beach	JTMD	113	KU-d13506	*Ectocarpus* cf. *fasciculatus*	*Ectocarpus* sp.
8-Sep-14	Stackpole walk-out, Willapa Bay	WA	6	KU-d13559	*Callithamnion* cf. *corymbosum*	*Callithamnion corymbosum*
12-Aug-14	Grays Harbor jetty - outside	WA	92	KU-d13560	*Carpopeltis* or *Prionitis*	*Grateloupia* sp.
14-Jul-10	Otter Crest	OR	119	KU-d13562	*Ptilota filicina*	*Ptilota filicina*
17-May-10	Seal Rock	OR	120	KU-d13563	*Ptilota filicina*	*Ptilota filicina*
08-Sep-14	Stackpole walk-out, Willapa Bay	WA	2	KU-d13564	*Ceramium* cf. *gardneri*	*Ceramium pacificum*
08-Sep-14	Brighton	OR	63	KU-d13565	*Ceramium gardneri*	*Ceramium* sp.
12-Aug-14	Grays Harbor floating docks	WA	77	KU-d13567	*Ceramium* #1	*Ceramium* sp.
12-Aug-14	Grays Harbor floating docks	WA	80	KU-d13568	*Ceramium* #2	*Ceramium* sp.
12-Aug-14	Grays Harbor jetty - outside	WA	95	KU-d13569	*Ceramium* sp.	*Ceramium pacificum*
12-Aug-14	Grays Harbor Jetty, channel	WA	102	KU-d13570	*Ceramium* sp.	*Membranoptera platyphylla*
07-Sep-14	Stony Point Sands, Willapa Bay	WA	32	KU-d13571	*Gracilaria* sp. (*vermiculophylla?*)	*Gracilaria vermiculophylla*
17-Jan-15	South Beach, inner jetty	OR	121	KU-d13572	*Gracilariopsis* cf. *andersonii*	*Gracilariopsis andersonii*
11-Jul-13	Lighthouse Point Beach, Cape Arago	WA	115	KU-d13574	*Ulva simplex*	*Ulva compressa*
11-Jul-13	Lighthouse Point Beach, Cape Arago	WA	116	KU-d13575	*Ectocarpus commensalis*	*Ectocarpus* sp.

11-Jul-13	Lighthouse Point Beach, Cape Arago	WA	117	KU-d13576	*Ectocarpus commensalis*	*Ectocarpus* sp.
08-Sep-14	Stackpole walk-out, Willapa Bay	WA	4	KU-d13580	*Neosiphonia* 2	*Neosiphonia harveyi*
08-Sep-14	Stackpole walk-out, Willapa Bay	WA	8	KU-d13581	*Neosiphonia* 3	*Neosiphonia harveyi*
08-Sep-14	Jetty Fishery	OR	67	KU-d13582	*Pterosiphonia bipinnata*	*Pterosiphonia bipinnata*
07-Sep-14	Oregon Shores	WA	52	KU-d13584	*Polysiphonia*	*Polysiphonia* sp.
08-Sep-14	Grays Harbor, SW	WA	40	KU-d13585	*Polysiphonia* cf. *paniculata*	*Polysiphonia* sp.
12-Aug-14	Grays Harbor Jetty, outside	WA	96	KU-d13586	*Membranoptera* cf. *dimorpha*	*Membranoptera platyphylla*
08-Sep-14	Grays Harbor, SW	WA	45	KU-d13587	*Hymenena cuneifolia*	*Hymenena flabelligera*
07-Sep-14	Stony Point Sands, Willapa Bay	WA	34	KU-d13588	*Dasya* sp.	*Dasya baillouviana*
08-Sep-14	Stackpole walk-out, Willapa Bay	WA	3	KU-d13589	*Dasya* sp.	*Dasya baillouviana*
02-Mar-15	Manzanita, OR #1 - blue plastic basket	JTMD	125	KU-d13591	*Halymenia* sp.	*Schizymenia dubyi*
02-Mar-15	Manzanita, OR #1 - blue plastic basket	JTMD	126	KU-d13592	*Ulva* sp.	*Ulva* cf. *linza*
02-Mar-15	Manzanita, OR #1 - blue plastic basket	JTMD	127	KU-d13593	*Petalonia fascia*	*Petalonia fascia*
02-Mar-15	Manzanita, OR #2 - blue plastic basket	JTMD	128	KU-d13594	*Petalonia fascia*	*Petalonia fascia*
02-Mar-15	Manzanita, OR #2 - blue plastic basket	JTMD	129	KU-d13595	*Polysiphonia senticulosa*	*Polysiphonia morrowii*
02-Mar-15	Long Beach #9 -- white plastic tray	JTMD	130	KU-d13596	*Red unicell*	*Tsunamia transpacifica*
02-Mar-15	Long Beach #11 -- black buoy	JTMD	131	KU-d13597	*Ulva simplex*	*U. prolifera*
02-Mar-15	Long Beach #11 -- black buoy	JTMD	132	KU-d13598	*Ulva simplex*	*U. prolifera*
02-Mar-15	Long Beach #11 -- black buoy	JTMD	134	KU-d13600	*Ulva simplex*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
02-Mar-15	Long Beach #11 -- black buoy	JTMD	135	KU-d13601	*Ectocarpus* sp.	*Ectocarpus* sp.
	Grays Harbor Jetty	WA	158	KU-d13807	*Blidingia minima minima*	*Blidingia* sp.
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	201	KU-d13808	*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	202	KU-d13809	*Ulva* cf. *prolifera*	*Ulva compressa*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	203	KU-d13810	*Chondrus* sp.	*Chondrus giganteus*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	204	KU-d13811	*Scytosiphon* sp.	*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	205	KU-d13812	*Petalonia fascia*	*Petalonia fascia*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	206	KU-d13813	*Ulva* cf. *australis*	*Ulva pertusa/australis*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	207	KU-d13814	*Ulva* cf. *intestinalis?*	*Ulva compressa*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	208	KU-d13815	*Pyropia* sp.	*Pyropia* sp.
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	209	KU-d13816	*Pyropia* sp.	*Pyropia* sp.
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	210	KU-d13817	*Ectocarpus* sp.	*Feldmannia mitchelliae*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	211	KU-d13818	*Ulva* cf. *intestinalis?*	*Ulva compressa*

9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	212	KU-d13819		*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	213	KU-d13820	*Feldmannia* cf. *hemisphica?*	*Ectocarpus* sp.
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	214	KU-d13821	*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	215	KU-d13822	*Petalonia fascia*	*Petalonia fascia*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	216	KU-d13823	*Petalonia zosterifolia?*	*Petalonia zosterifolia*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	217	KU-d13824	*Scytosiphon lomentaria*	*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	218	KU-d13825	*Punctaria cf. latifolia*	*Punctaria latifolia*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	219	KU-d13826	*Punctaria* sp.	*Punctaria latifolia*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	222	KU-d13828	*Feldmannia* sp.	*Feldmannia mitchelliae*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	223	KU-d13829	*Ectocarpus* sp.	*Ectocarpus* sp.
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	225	KU-d13830	*Scytosiphon*	*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	226	KU-d13831	*Scytosiphon* cf. *lomentaria*	*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	228	KU-d13832	*Ulva cf. simplex*	*Ulva compressa*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	229	KU-d13833	*Scytosipiphon*	*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	230	KU-d13834	*Ulva* cf. *australis*	*Ulva pertusa/australis*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	233	KU-d13836	*Ulva* cf. *japonica?*	*Ulva pertusa/australis*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	234	KU-d13837	*Ectocarpus* cf. *commensalis*	*Ectocarpus* sp.
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	235	KU-d13838	*Feldmannia* cf. *mitchelliae*	*Feldmannia mitchelliae*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	237	KU-d13839	*Chondrus?*	*Chondrus giganteus*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	238	KU-d13840	*Punctaria*	*Punctaria latifolia*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	239	KU-d13841	*Scytosiphon* sp.	*Scytosiphon lomentaria*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	240	KU-d13842	*Ulva*	*Ulva pertusa/australis*
9 or 10-Apr-15	Seal Rock Boat, off shore/SB marina	JTMD	244	KU-d13843	*Chondrus*	*Chondrus giganteus*
2-May-19	Long Beach dock fragment	JTMD	365	KU-d13844	*Blidingia minima minima*	*Blidingia minima*
2-May-19	Long Beach dock fragment	JTMD	367	KU-d13845	*Scytosiphon* cf. *gracilis?*	*Petalonia zosterifolia*
2-May-19	Long Beach dock fragment	JTMD	368	KU-d13846	*Bangia* sp.	*Bangia* sp.
2-May-19	Long Beach dock fragment	JTMD	369	KU-d13847	*Bangia* sp.	*Bangia* sp.
20-May-19	South Beach pilings	OR	370	KU-d13848	*Bangia* sp.	*Bangia* sp.
20-May-19	South Beach docks	OR	371	KU-d13849	*Halymenia* sp.	*Grateloupia* sp.
20-May-19	South Beach docks	OR	372	KU-d13850	*Blidingia subsalsa*	*Blidingia* sp.
20-May-19	South Beach docks	OR	373	KU-d13851	*Polysiphonia macounii*	*Polysiphonia brodiei*
19-May-19	Boiler Bay	OR	374	KU-d13852	*Acinetospora* sp.	*Pylaiella washingtoniensis*

13-May-19	Seaview Boat 672	JTMD	375	KU-d13853	*Ulva* cf. *simplex*	*Ulva compressa*
13-May-19	Seaview Boat 672	JTMD	376	KU-d13854	*Ulva simplex/intestinalis*	*Ulva compressa*
13-May-19	Seaview Boat 673	JTMD	377	KU-d13855	*Ulva simplex*	*Ulva compressa*
13-May-19	Seaview Boat 673	JTMD	378	KU-d13856	*Petalonia zosterifolia ?*	*Petalonia zosterifolia*
13-May-19	Seaview Boat 673	JTMD	379	KU-d13857	*Petalonia fascia*	*Petalonia fascia*
13-May-19	Seaview Boat 673	JTMD	380	KU-d13858	*Petalonia zosterifolia*	*Petalonia zosterifolia*
13-May-19	Seaview Boat 674	JTMD	382	KU-d13860	*Petalonia zosterifolia*	*Scytosiphon lomentaria*
13-May-19	Seaview Boat 674	JTMD	383	KU-d13861	*Ectocarpus* with many plurilocs	*Ectocarpus* sp.
13-May-19	Seaview Boat 676	JTMD	384	KU-d13862	*Ulva simplex*	*Ulva compressa*
13-May-19	Seaview Boat 676	JTMD	385	KU-d13863	*Ulva simplex*	*Ulva compressa*
13-May-19	Seaview Boat 677	JTMD	386	KU-d13864	*Petalonia zosterifolia*	*Petalonia zosterifolia*
13-May-19	Seaview Boat 679	JTMD	388	KU-d13866	*Petalonia* cf. *fascia*	*Petalonia fascia*
13-May-19	Seaview Boat 680	JTMD	389	KU-d13867	*Petalonia* cf. *fascia*	*Petalonia fascia*
04-Jan-15	Long Beach, black float	JTMD	399	KU-d13879	*Sytosiphon* cf. *gracilis*	*Scytosiphon lomentaria*
04-Jan-15	Long Beach, black float	JTMD	404	KU-d13880	*Feldmannia irregularis*	*Feldmannia irregularis*
04-Jan-15	Long Beach, black float	JTMD	405	KU-d13881	*Ectocarpus*	*Ectocarpus* sp.
09-Apr-15	Nye Beach Turnaround	JTMD	406	KU-d13882	*Ectocarpus commensalis/Kuckuckia*	*Ectocarpus* sp.
04-Jan-15	Long Beach, black float	JTMD	407	KU-d13883	*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
04-Jan-15	Long Beach, black float	JTMD	408	KU-d13884	*Ectocarpus commensalis/Kuckuckia*	*Feldmannia mitchelliae*
04-Jan-15	Long Beach, black float	JTMD	409	KU-d13885	*Scytosiphon lomentaria*	*Scytosiphon lomentaria*
04-Jan-15	Long Beach, black float	JTMD	398	KU-d13899	*Ulva compressa*	*Ulva compressa*
25-Mar-15	Grays Harbor, oyster 3,WA	WA	146	KU-d13995	*Bryopsis hypnoides*	*Bryopsis* cf. *plumosa*
26-Mar-15	GH, jetty channel,WA	WA	157	KU-d13996	*Ulva* cf. *lactuca*	*Ulva californica*
26-Mar-15	GH, jetty channel,WA	WA	158	KU-d13997	*Blidingia minima minima ?*	*Blidingia* sp.
27-Mar-15	GH, Westport docks,WA	WA	159	KU-d13998	*Bryopsis*	*Bryopsis* sp.
27-Mar-15	GH, Westport docks,WA	WA	163	KU-d13999	*Ulva* cf. *lactuca*	*Ulva pertusa/australis*
27-Mar-15	GH, Westport docks, WA	WA	165	KU-d14000	*Scytosiphon lomentaria*	*Scytosiphon lomentaria*
28-Mar-15	WB, Port of Peninsula,WA	WA	170	KU-d14002	*Blidingia* sp.	*Blidingia* sp.
28-Mar-15	WB, Port of Peninsula, WA	WA	172	KU-d14003	*Petalonia fascia*	*Petalonia fascia*
27-Mar-15	GH, Westport docks, WA	WA	177	KU-d14004	*Scytosiphon*	*Scytosiphon lomentaria*
27-Mar-15	GH, boat launch, WA	WA	185	KU-d14006	*Gayralia oxyspermum*	*Gayralia oxyspermum*
28-Mar-15	WB, Port of Peninsula,WA	WA	194	KU-d14008	*Bryopsis hypnoides*	*Bryopsis* sp.

17-Jun-15	Jetty Fishery,OR	OR	249	KU-d14009	*Petalonia fascia*	*Petalonia fascia*
17-Jun-15	Jetty Fishery,OR	OR	251	KU-d14010	*Bryopsis plumosa*	*Bryopsis* cf. *plumosa*
17-Jun-15	Brighton,OR	OR	258	KU-d14011	*Petalonia fascia*	*Petalonia fascia*
18-Jun-15	GH Jetty,WA	WA	264	KU-d14012	*Blidingia minima*	*Blidingia minima*
18-Jun-15	GH Jetty, WA	WA	265	KU-d14013	*Ulva lactuca*	*Ulva lobata*
18-Jun-15	Brady's Oyster Farm, WA	WA	266	KU-d14014	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
18-Jun-15	Brady's Oyster Farm, WA	WA	267	KU-d14015	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
18-Jun-15	Brady's Oyster Farm,WA	WA	270	KU-d14016	*Ulva torta*	*Ulva torta*
19-Jun-15	S. Cove Oyster Farm, WA	WA	281	KU-d14017	*Ulva* sp.	*Ulva lactuca*
19-Jun-15	S. Cove Oyster Farm,WA	WA	282	KU-d14018	*Ulva linza*	*Ulva* cf. *linza*
19-Jun-15	S. Cove Oyster Farm, WA	WA	283	KU-d14019	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms, WA	WA	287	KU-d14020	*Ulva* cf. *lobata*	*Ulva lactuca*
20-Jun-15	N. Cove Oyster farms, WA	WA	288	KU-d14021	*Ulva torta*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms,WA	WA	289	KU-d14022	*Ulva torta*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms, WA	WA	292	KU-d14023	*Bryopsis hypnoides*	*Bryopsis* sp.
20-Jun-15	N. Cove Oyster farms, WA	WA	302	KU-d14025	*Ulva*	*Ulva* cf. *linza*
20-Jun-15	N. Cove Oyster farms, WA	WA	303	KU-d14026	*Ulva*	*Ulva lactuca*
20-Jun-15	N. Cove Oyster farms, WA	WA	304	KU-d14027	*Ulva flexuosa*	*Ulva* sp. 4 (in Ogawa *et al.* 2013)
20-Jun-15	N. Cove Oyster farms, WA	WA	305	KU-d14028	*Cladophora microcladioides*	*Cladophora albida*
20-Jun-15	N. Cove Oyster farms, WA	WA	312	KU-d14030	*Ulva prolifera*	*Ulva prolifera*
19-Jun-15	Westport docks, WA	WA	314	KU-d14032	*Percursaria percursa*	*Percursaria percursa*
19-Jun-15	Westport docks, WA	WA	334	KU-d14033	*Ulva* sp.	*Ulva pertusa/australis*
19-Jun-15	Westport docks, WA	WA	336	KU-d14034	*Ulva flexuosa, Chaetomorpha linum*	*Ulva torta*
19-Jun-15	Westport docks, WA	WA	337	KU-d14035	*Rosenvingiella radicans*	*Rosenvingiella radicans*
19-Jun-15	Westport docks, WA	WA	338	KU-d14036	*Gayralia oxyspermum* var. *?blytii*	*Gayralia oxyspermum*
19-Jun-15	Westport docks, WA	WA	339	KU-d14037	*Blidingia minima*	*Blidingia minima*
19-Jun-15	Westport docks, WA	WA	340	KU-d14038	*Blidingia minima var minima*	*Blidingia* sp.
17-Jun-15	Port of Peninsula, WA	WA	353	KU-d14044	*Petalonia fascia*	*Petalonia fascia*
17-Jun-15	Port of Peninsula, WA	WA	354	KU-d14045	*Ulva lactuca*	*Ulva pertusa/australis*
17-Jun-15	Port of Peninsula, WA	WA	355	KU-d14046	*Cladophora cfr. Laetivirens?*	*Cladophora vagabunda*
20-Jun-15	Ilwaco docks, WA	WA	360	KU-d14048	*Blidingia subsalsa*	*Blidingia* sp.
20-Jun-15	Ilwaco docks, WA	WA	361	KU-d14050	*Ulva prolifera*	*Ulva prolifera*

24-Mar-15	Grays Harbor, oyster2	WA	140	KU-d14214	*Ectcarpus* sp.	*Ectcarpus siliculosus*
24-Mar-15	Grays Harbor, oyster2	WA	141	KU-d14215	*Ectcarpus on Fucus*	*Pylaiella washingtoniensis*
24-Mar-15	Grays Harbor, oyster3	WA	142	KU-d14216	*Petalonia fascia*	*Petalonia fascia*
24-Mar-15	Grays Harbor, oyster3	WA	145	KU-d14217	*Ectcarpus* sp.	*Ectcarpus* sp.
24-Mar-15	Grays Harbor, oyster1	WA	150	KU-d14218	*Ectcarpus bushy*	*Ectcarpus* sp.
27-Mar-15	Ilwaco	WA	173	KU-d14221	*Pylaiella littoralis*	*Pylaiella* sp.
27-Mar-15	Ilwaco	WA	174	KU-d14222	*Ectcarpus -Pyaiella*	*Pylaiella washingtoniensis*
16-Jun-15	Jetty Fishery	OR	255	KU-d14224	*Ectcarpus*	*Ectcarpus* sp.
17-Jun-15	GH Jetty	WA	262	KU-d14225	*Hincksia granulosa*	*Hincksia granulosa*
18-Jun-15	S. Cove Oyster Farm	WA	274	KU-d14226	*Ectcarpus siliculosus?*	*Ectcarpus* sp.
18-Jun-15	S. Cove Oyster Farm	WA	277	KU-d14228	*Ectcarpus siliculosus?*	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	297	KU-d14229	*Ectcarpus* cf. *siliculosus*	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	299	KU-d14230	*Ectocarpales*	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	300	KU-d14231	*Ectcarpus pencillatus*	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	308	KU-d14232	*Ectcarpus* cf. *siliculosus*	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm	WA	309	KU-d14233	*Ectcarpus* cf. *siliculosus*	*Ectcarpus* sp.
19-Jun-15	N. Cove Oyster Farm-drift	WA	6289	KU-d14234	*Alaria marginata*	*Alaria* sp.
18-Jun-15	Westport docks	WA	6275	KU-d14235	*Srgassum muticum*	*Srgassum muticum*
16-Jun-15	Port of Peninsula	WA	351	KU-d14236	*Ectcarpus siliculosus?*	*Ectcarpus* sp.
02-Feb-16	South Beach Marina, Yaquina Bay	OR	493	KU-d14237	*Ulva* cf. *lactuca*	*Ulva pertusa/australis*
03-Feb-16	South Beach Marina pilings	OR	494	KU-d14238	*Blidingia* cf. *subsalsa*	*Blidingia* sp.
5-Jun-15	Agate Beach Dock	JTMD	436		*Polysiphonia* sp.	*Polysiphonia* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	625		*Cladophora* 1	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	626		*Cladophora* 2	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	627		*Cladophora* 1	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	628		*Polysiphonia scopulorum* var. *villum?*	*Polysiphonia* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	629		*Polysiphonia*	*Polysiphonia* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	630		*Petalonia fascia*	*Petalonia fascia*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	631		*Cladophora* 2	*Cladophora vagabunda*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	632		*Cladophora* 3	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	633		*Feldmannia intermedia?*	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	635		*Feldmannia mitchelliae*	*Feldmannia mitchelliae*

22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	636		*Colaconema daviesii*	*Colaconema* sp.
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	638		*Feldmannia* sp.	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	640		*Feldmannia* sp.	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	641		*Cladophora dalmatica*	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	644		*Feldmannia* sp.	*Feldmannia mitchelliae*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	645		*Cladophora albida*	*Cladophora albida*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	646		*Ulva compressa*	*Ulva compressa*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	647		*Ulva compressa*	*Ulva compressa*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	648		*Ulva compressa*	*Ulva compressa*
22-Mar-16	Horsfall Beach 2 derelict boat	JTMD	651		*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
28-Mar-16	Roads End Derelict boat	JTMD	662		*Petalonia fascia*	*Petalonia fascia*
28-Mar-16	Roads End Derelict boat	JTMD	663		*Scytosiphon lomentaria*	*Scytosiphon lomentaria*
28-Mar-16	Roads End Derelict boat	JTMD	664		*Petalonia zosterifolia*	*Petalonia zosterifolia*
28-Mar-16	Roads End Derelict boat	JTMD	665		*Ulva compressa?*	*Ulva compressa*
28-Mar-16	Roads End Derelict boat	JTMD	666		*Ulva linza*	*Ulva* cf. *prolifera*
28-Mar-16	Roads End Derelict boat	JTMD	667		*Ulva linza*	*Ulva* cf. *prolifera*
28-Mar-16	Roads End Derelict boat	JTMD	669		*Colaconema thurettii*	*Colaconema* sp.
28-Mar-16	Roads End Derelict boat	JTMD	674		*Colaconema* sp.	*Colaconema* sp.
28-Mar-16	Roads End Derelict boat	JTMD	675		*Polysiphonia morrowii?*	*Polysiphonia morrowii*
28-Mar-16	Roads End Derelict boat	JTMD	679		*Sphacelaria rigidula*	*Sphacelaria rigidula*
28-Mar-16	Roads End Derelict boat	JTMD	685		*Feldmannia mitchelliae?*	*Feldmannia mitchelliae*
28-Mar-16	Roads End Derelict boat	JTMD	686		*Ectocarpus* sp.	*Ectocarpus* sp.
28-Mar-16	Roads End Derelict boat	JTMD	688		*Feldmannia* sp.	*Feldmannia mitchelliae*
28-Mar-16	Roads End Derelict boat	JTMD	689		*Sphacelaria* sp.	*Polysiphonia koreana*
28-Mar-16	Roads End Derelict boat	JTMD	690		*Ectocarpus* sp.	*Ectocarpus* sp.
28-Mar-16	Roads End Derelict boat	JTMD	691		*Feldmannia* sp.	*Feldmannia mitchelliae*
28-Mar-16	Roads End Derelict boat	JTMD	692		*Punctaria latifolia*	*Punctaria latifolia*
28-Mar-16	Roads End Derelict boat	JTMD	693		*Feldmannia?*	*Feldmannia mitchelliae*
28-Mar-16	Roads End Derelict boat	JTMD	694		*Feldmannia?*	*Feldmannia mitchelliae*
28-Mar-16	Roads End Derelict boat	JTMD	695		*Ectocarpus* sp.	*Ectocarpus* cf. *commensalis*
28-Mar-16	Roads End Derelict boat	JTMD	697		*Polysiphonia morrowii*	*Polysiphonia morrowii*
28-Mar-16	Roads End Derelict boat	JTMD	698		*Ectocarpus* sp.	*Ectocarpus* cf. *commensalis*

28-Mar-16	Roads End Derelict boat	JTMD	699		*Ectocarpus* sp.	*Ectocarpus* sp.
28-Mar-16	Roads End Derelict boat	JTMD	700		*Feldmannia* sp.	*Ectocarpus* sp.
28-Mar-16	Roads End Derelict boat	JTMD	701		*Petalonia zosterifolia*	*Petalonia zosterifolia*
28-Mar-16	Roads End Derelict boat	JTMD	702		*Cladophora albida*	*Cladophora* sp.
28-Mar-16	Roads End Derelict boat	JTMD	703		*Punctaria latifolia*	*Punctaria latifolia*
26-Mar-16	Forks derelict boat	JTMD	707		*Ectocarpus* sp.	*Ectocarpus* cf. *commensalis*
26-Mar-16	Forks derelict boat	JTMD	708		*Petalonia zosterifolia?*	*Scytosiphon lomentaria*
	Sixes River Derelict boat	JTMD	710		*Grateloupia/Halymenia*	*Grateloupia turuturu*
	Sixes River Derelict boat	JTMD	711		*Cladophora* 1	*Cladophora albida*
	Sixes River Derelict boat	JTMD	712		*Cladophora* 2	*Cladophora albida*
	Sixes River Derelict boat	JTMD	713		*Sphacelaria rigidula* 1	*Sphacelaria rigidula*
	Sixes River Derelict boat	JTMD	714		*Sphacelaria rigidula* 2	*Sphacelaria rigidula*
	Sixes River Derelict boat	JTMD	716		*Mutimo cylindricus*	*Mutimo cylindricus*
	Sixes River Derelict boat	JTMD	717		*Blidingia minima minima*	*Blidingia minima*
	Sixes River Derelict boat	JTMD	718		*Cryptopleura*	*Cryptopleura ruprechtiana*
	Sixes River Derelict boat	JTMD	719		*Ectocarpus* sp.	*Kuckuckia* sp.
	Sixes River Derelict boat	JTMD	721		*Halymenia* sp.	*Grateloupia turuturu*
	Sixes River Derelict boat	JTMD	722		*Pyropia* sp.	*Pyropia conwayae*
	Sixes River Derelict boat	JTMD	723		*Sphacelaria* cf. *rigidula*	*Sphacelaria rigidula*
	Sixes River Derelict boat	JTMD	724		*Feldmannia mitchelliae*	*Feldmannia mitchelliae*
	Sixes River Derelict boat	JTMD	726		*Colaconema* sp.	*Colaconema* sp.
	Sixes River Derelict boat	JTMD	727		*Petalonia fascia*	*Petalonia fascia*
	Sixes River Derelict boat	JTMD	728		*Sphacelaria* sp.	*Sphacelaria rigidula*
		OC	731		*Blidingia minima vexata*	*Blidiniga* sp.
		OC	733		*Blidingia minima*	*Blidiniga* sp.
		OC	734		*Polysiphonia* 1	*Polysiphonia* sp.
		OC	735		*Polysiphonia* 2	*Polysiphonia* sp.
		PP	747		*Ulva* sp.	*Ulva pertusa/australis*
		PP	749		*Cladophora albida?*	*Cladophora opaca*
		PP	750		*Cladophora* sp.	*Cladophora opaca*
		ILW	751		*Ulva intestinalis*	*Ulva intestinalis*
		ILW	752		*Gayralia?*	*Gayralia oxysperma*

		JTMD	620		*Petroderma maculiforme*	*Petroderma maculiforme*
	Falcon Cove boat	JTMD	750		*Kuckuckia* or *Ectocarpus*	*Ectocarpus* sp.
	Falcon Cove boat	JTMD	751		*Cladophora* sp.	*Cladophora vagabunda*
	Falcon Cove boat	JTMD	752		*Kuckuckia* or *Ectocarpus*	*Ectocarpus* sp.
	Falcon Cove boat	JTMD	753		*Kuckuckia* or *Ectocarpus*	*Ectocarpus* sp.
		JTMD	GIH5778		*Analipus japonica*	*Analipus japonica*
		OR	GIH4203		*Analipus japonica*	*Analipus japonica*
	Agate Beach Dock	JTMD	GIH5790a	KU-d15599	*Undaria pinnatifida*	*Undaria pinnatifida*
	Agate Beach Dock	JTMD	GIH5788	KU-d15600	*Costaria costata*	*Costaria costata*
04-Jun-04	Boilger Bay	OR	GIH1932	KU-d15601	*Costaria costata*	*Costaria costata*
09-Aug-06	N. Boaidmon	OR	GIH2787	KU-d15602	*Costaria costata*	*Costaria costata*
24-Jun-98	Green Island	AK	98-pws-128	KU-d15603	*Costaria costata*	*Costaria costata*
30-Oct-06	Tatoosh Island	WA	GIH2487	KU-d15604	*Alaria*	*Alaria* sp.

THEME IV – Characteristics of Japanese Tsunami Marine Debris Species

Chapter 11: Survival and fitness of Japanese Tsunami Marine Debris rafting species[6]

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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 Tsunami of 2011. We surveyed the settlement and 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 *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. 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 indicated that at least some biota settled on these items after the tsunami. Variations in size, growth rate, and reproductive state between arrivals in North American and Hawaii suggest that the drift path affected fitness during transit. Using stable isotope analysis, we showed that JTMD mussels were growing during their oceanic transit and arrived in many locations capable or reproduction even after 40 months at sea.

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[6] A version of this chapter first appeared in PICES Press Vol 24, No 1 “The mussel *Mytilus galloprovincialis* on Japanese tsunami marine debris: A potential model species to characterize a novel transport vector”. A subsequent version will be submitted to a peer-reviewed journal.

Non-native peracaridan crustaceans (including gammarid and caprellid amphipods, isopods, and tanaids) on drifting objects began to arrive on 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 and also 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 Gallo mussel, *Mytilus galloprovincialis*, is a non-native species that is established in Japan and was common on JTMD, present on more than 60% of the items that we classified as JTMD. As this species is a predominantly intertidal, filter-feeder 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 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 11 of those JTMD items by completing chemical and structural 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. 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 US 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. Drifting 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 analyses 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.

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. We completed the size and reproduction assessment on over 1000 individuals.

We conducted structural and chemical analyses on the *Mytilus* shells of a subset of individuals across the observed size range from representative debris items collected during the Spring 2014 pulse of JTMD vessels. These efforts built upon prior work in which we quantified variation in the ratio of barium:calcium (Ba:Ca) profiles across the growth axis of the mussels and thus add to our relatively comprehensive picture of the size, growth, and dispersal history of *Mytilus* arriving on selected JTMD items from June 2012 through June 2014. 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. The premise of this analysis relies on the fact that coastal waters typically display higher concentrations of many trace metals, including barium (Ba), than offshore, open ocean waters. 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 US coastal waters (relatively high Ba) if adequate shell growth occurred.

For chemical and structural 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) 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 potential to establish new populations.

Results

Mussel size and reproduction

Based on 20 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 2012-2013, the mean size of *Mytilus* increased by 10 to 19 mm/year 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 2 or more years after the tsunami. However, in 2014, there was no observed increased in size of *Mytilus* collected in Oregon and Washington. Furthermore, mussels with mature or maturing gametes continued to arrive through 2014. For 35 JTMD items collected from 2012-2014, reproductive individuals were observed in Hawaii (<17% of all mussels examined) and Oregon and Washington (>60%) (Figure 11-3). The arrival of reproductive individuals indicates that mussels may have released gametes in the coastal waters of these regions.

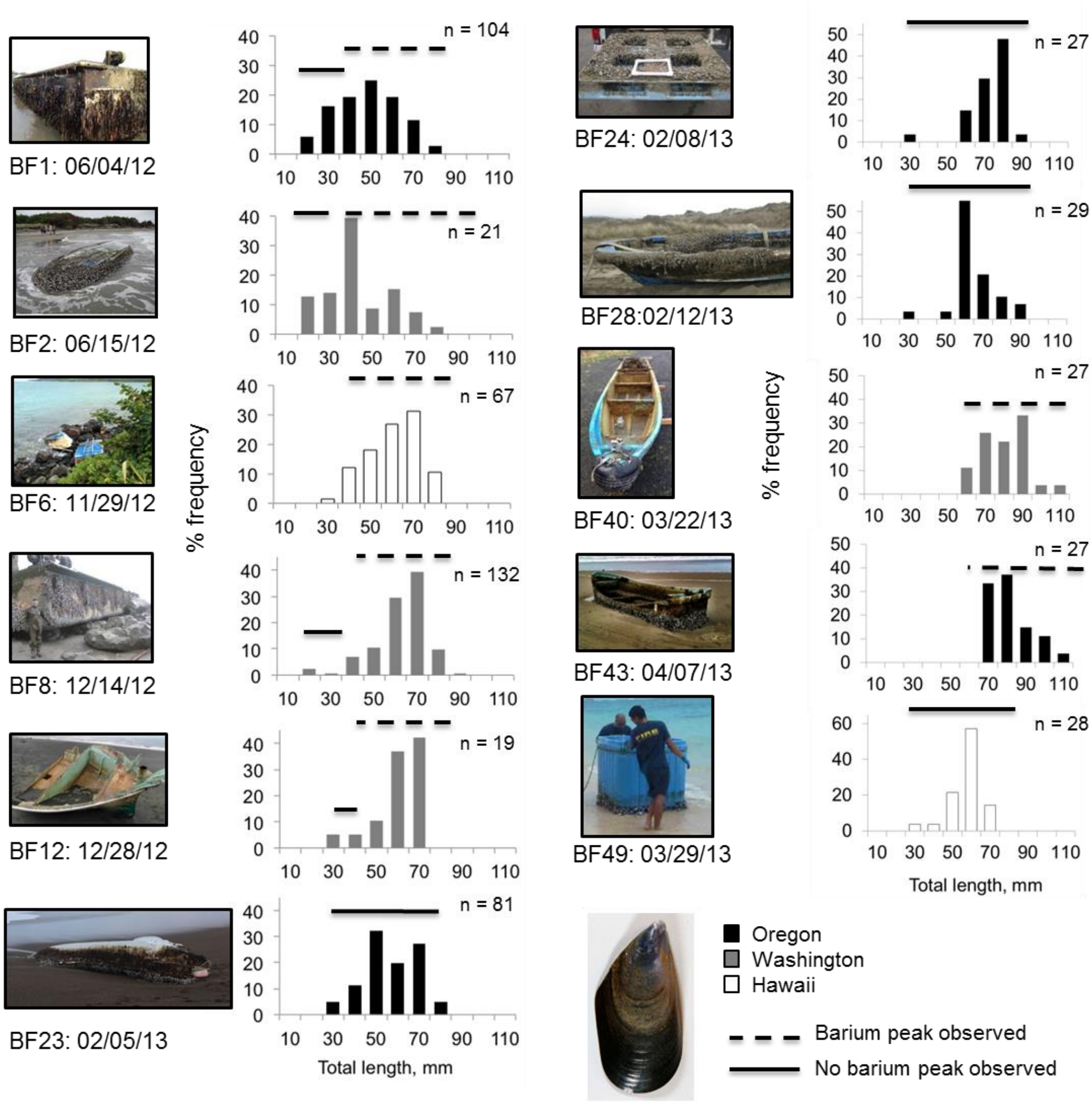

Figure 11-1. Size frequency distribution for total shell length (mm) of *Mytilus* sp. on JTMD items. Each sampled item was given a unique identification (BF1, etc). The estimated date of item arrival on local beach is included along with sample size for each item. The lines above each histogram indicate the size range across which a prominent peak in shell Ba/Ca was observed (dashed lines) or not (solid lines).

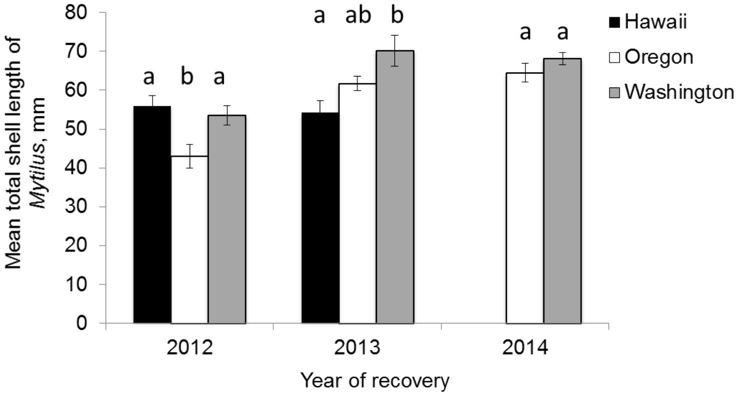

Figure 11-2. Mean length (±2 SE) of *Mytilus* recovered on JTMD. Letters indicate groups that are statistically similar within years. Across years, *Mytilus* from Hawaii were equivalent in size in 2012 and 2013 whereas Oregon and Washington samples increased in size in 2013, compared with 2012, but then stabilized. Washington samples were larger than Oregon and Hawaii in 2012 and 2013 but not 2014. Total n = 1067.

Interestingly, mean size of arriving *Mytilus* was smallest in Hawaii with no significant variation between 2012 and 2013 collections. However, shell size increased in Oregon and Washington between 2012 and 2013 but appears to have stabilized, as the sizes of 2014 collections were similar to 2013 (Figure 11-3). Furthermore, reproductive individuals consistently arrived throughout our collections from 2012 to 2014. 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 coast.

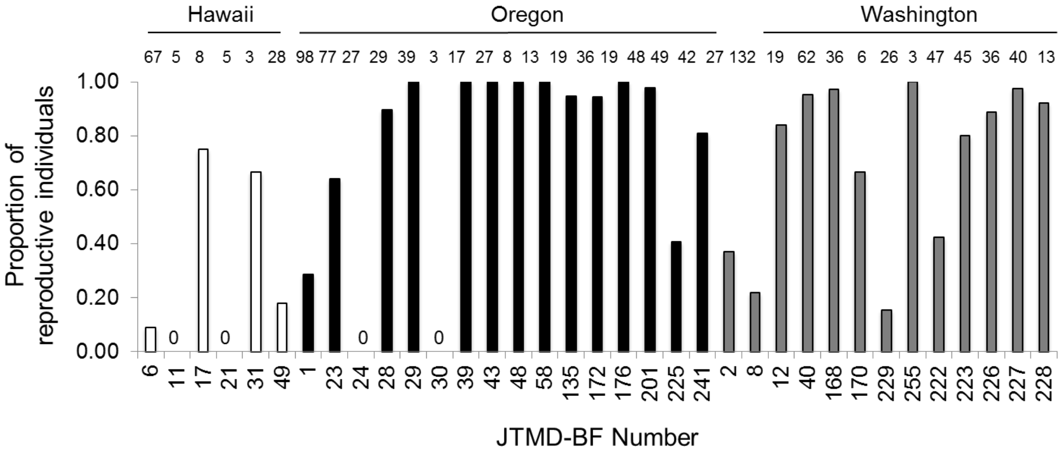

Figure 11-3. Proportion of *Mytilus* with mature or maturing gametes on various JTMD-BF items recovered in Hawaii, Oregon, and Washington. Sample sizes are included at top of graph. JTMD-BF numbers are along the x-axis and are arranged chronologically within each region with the earliest recoveries (2012) 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 (Figure 11-4). The patterns of shell Ba/Ca were remarkably consistent within individuals of similar sizes on the same JTMD item. Interestingly, for many JTMD items, we detected a peak (usually >2x background) in Ba/Ca, followed by a period of low Ba/Ca, 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 remains 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 are well-correlated with water Ba/Ca levels. In this instance, it is possible that the peaks observed in so many 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 northwest 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) northeast Pacific coastal water growth identified as the region with gradual increase in shell Ba/Ca at the outer edge of each shell. We then estimated the total shell length at distinct points in time based on back-calculation models of umbo width and total shell length ($R^2 > 0.75$) (Figure 11-4). This approach allowed us to generate growth estimates (mm/day) for individual *Mytilus* shells during oceanic transit (low shell Ba/Ca). Additionally, we estimated 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.

The JTMD *Mytilus* grew an average of 0.06 mm/day (0.017 2SE) during transit and displayed variable shell growth (1 to 23 mm) during coastal residency in the northeast Pacific (Figure 11-5). Therefore, although slower than growth rates attained in coastal locations or culture settings (~0.12–0.16 mm/d) (Peteiro *et al*. 2006; Cubillo *et al*. 2012), the JTMD mussels were growing during their oceanic transit and arrived in many locations capable or reproduction after 15 to 40+ months at sea.

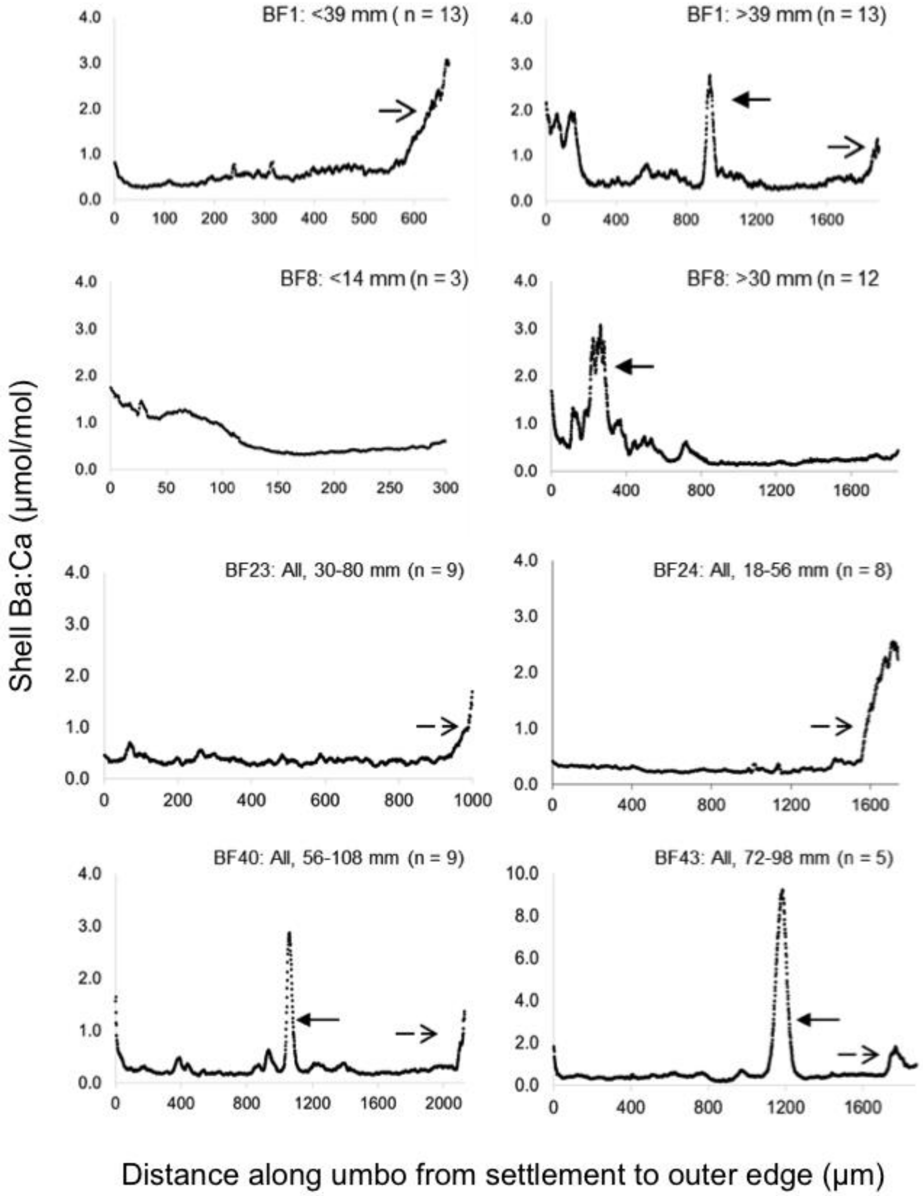

Figure 11-4. Representative Ba/Ca profiles across the umbo growth axis for *Mytilus* from selected JTMD BF items. Note for BF1 (Misawa Dock 1), BF2 (skiff), and BF8 (Misawa Dock3), the smaller shells do not display any peak in shell Ba/Ca prior to the gradual increase at the outer shell edge. The solid arrow indicates the initial Ba/Ca peak that is interpreted as occurring in the northwest Pacific, potentially related to the tsunami, and the open arrow is interpreted as arrival in Pacific coastal waters of North America.

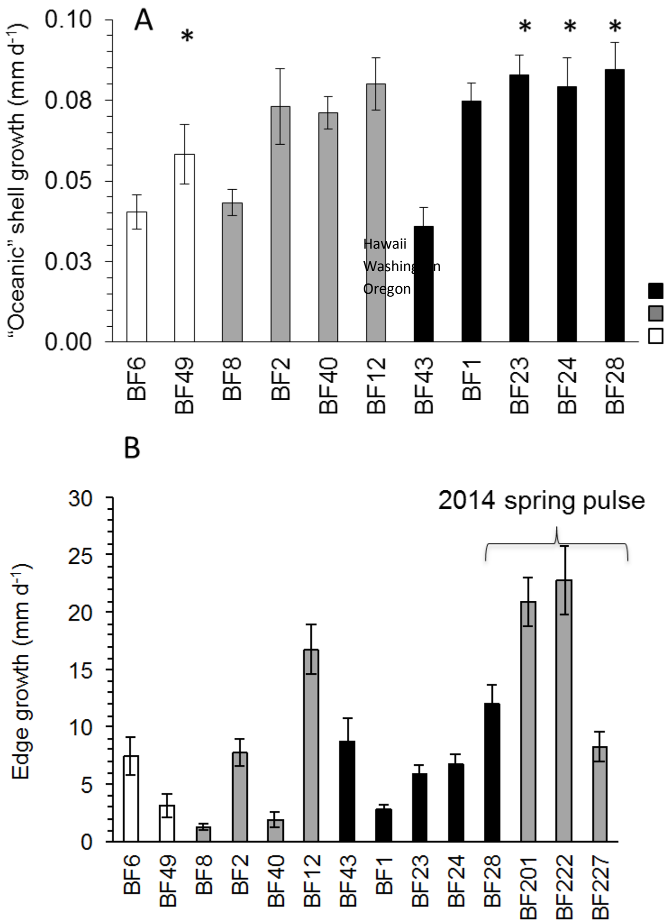

Figure 11-5. (A) Mean (±2 SE) "oceanic" shell growth of *Mytilus* based on chemical (Ba/Ca) and structural analysis of shells. Growth was estimated based on an empirical relationship between umbo width and total shell length for each debris item. Oceanic growth was defined as all shell deposition prior to gradual elevation of Ba/Ca at outer shell edge or, for those individuals that displayed a peak in Ba/Ca, the shell deposition after the peak in shell Ba/Ca to the elevation of shell Ba/Ca at the outer edge, indicative of arrival in northeast Pacific coastal waters. The total oceanic growth was divided by the days between the tsunami (March 11, 2011) and the date of recovery for each JTMD item. Those BF items with an "*" did not display a marked peak in Ba/Ca prior to the shell edge. (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 shell deposition during periods with moderately elevated Ba/Ca, presumably indicative of northeast Pacific coastal waters.

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 and two of the isopods species are new records for North America: *Ampithoe koreana*, *Caprella cristibrachium, Gammaropsis japonica*, *Dynoides spinipodus*, *Ianiropsis derjugini* and *Munna japonica* (recognized from a low quality specimen) (Table 11-1). Red species are unclear taxonomic groups. We assigned the known range of the species identified: 13 of the 22 species identified were previously known from the Northeast Pacific.

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

	Species	JTMD	Japan	Hawaii	Pacific North America	"Global"
Amphipoda	*Allorchestes angusta*	X		X	X	
	Ampithoe koreana	X	X			
	Ampithoe valida	X	X	X	X	X
	Ampithoe lacertosa	X		X	X	
	Gammaropsis japonicus	X				
	Jassa marmorata	X	X	X	X	
	Jassa carltoni	*x*			*x*	
	Jassa slatteryi	*x*	*x*	*x*	*x*	
	Jassa staudeyi	*x*	*x*	*x*	*x*	
	Stenothoe crenualata	X				X
	Stenothoe dentirama	*x*				
	Stenothoe gallenis	*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 serricaudis	X			X	X
	Ianiropsis derjugini	X				
	Munna japonica	X				

The size frequencies of these crustaceans revealed multiple overlapping cohorts within sexes (Figure 11-6). Single specimens from individual objects were unsuited for size analyses. However, we did not find large populations lacking in either juveniles or reproductive adults. Recent trophic conditions surrounding the JTMD objects appear to have been suitable for long term persistence. However, for example, the general differences between items BF-23 (a Japanese vessel that landed in Oregon in February 2013) and 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 frequencies of 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. However, the populations surviving ocean crossing could have high potential to invade North American ecosystems.

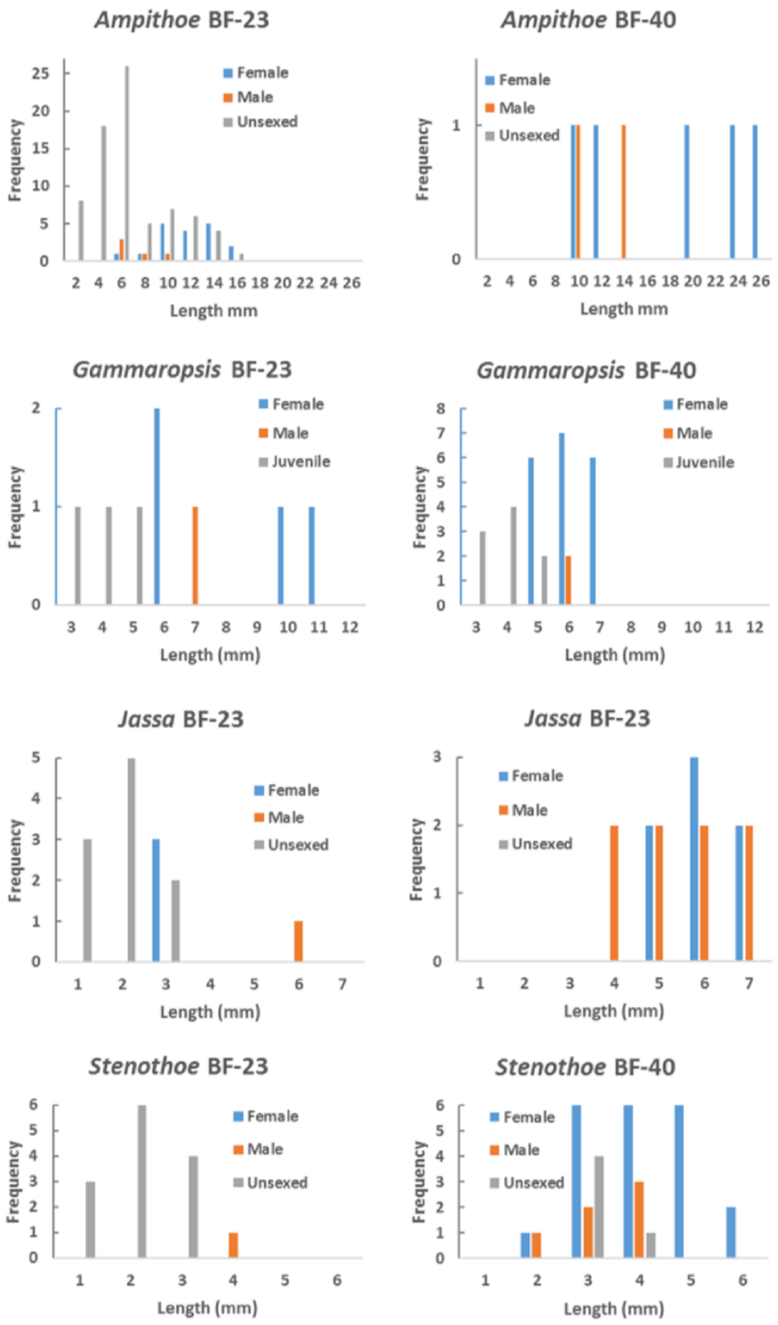

Figure 11-6. Length frequencies of male, female and juvenile *Ampithoe*, *Gammaropsis*, *Jassa* and *Stenothoe* from JTMD objects BF-23 and BF-40.

Discussion

In summary, we used the Gallo mussel *M. galloprovincialis* to provide information on the settlement and growth history of biota successfully transported across the Pacific on debris generated from the Great 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 coastal waters of the US 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 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*, *Caprella cristibrachium*, *Gammaropsis japonica*, *Dynoides spinipodus*, *Ianiropsis derjugini* and *Munna japonica* (recognized from a poor 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.

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THEME IV – Characteristics of Japanese Tsunami Marine Debris Species

Chapter 12: Distributional, environmental and life history attributes of Japanese Tsunami Marine Debris biota[7]

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Abstract

Almost 380 species 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, there is a lack of information on the life history, environmental, and distributional characteristics of these JTMD species. Project ADRIFT (Assessing the Debris-Related Impact of Tsunami) 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 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. The 135 species included in this analysis represent 12 phyla, with Mollusca, Crustacea, and Bryozoa each contributing slightly over 20% of the total. The reported native realm for this group of species covers the globe, ranging from the Southern Ocean to the Arctic. However, the majority are native to the northwest Pacific, followed by northeast Pacific, and the Central Indo-Pacific. Additionally, most species have no prior invasion history (>50%) while the remainder have a documented invasion history (23%), are cryptogenic (an unknown origin; 14%), or have an unclear establishment status (4%). Our quantitative analysis indicated that the geographic distribution of cryptogenic species was statistically distinct from species with and without any invasion history, but there was no distributional difference between species with and without invasion history. We documented significant differences between species with and without invasion histories based on environmental and life history attributes.

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[7] A version of this chapter is in preparation for submission to a peer-reviewed journal.

Species with known invasion histories were distinguished by a greater occurrence on temperate reef habitat and artificial and hardpan substrates; they were more common in subtropical and tropical waters and more protected habitats; and they exhibited greater salinity tolerance. We then identified species with no prior invasion history whose attributes were most similar to those with known invasion history. This group included 45 species, and 20 of those are already reported to occur in the northeast Pacific. The remaining 25 species, which are most similar to JTMD species with invasion histories but not yet established in the northeast Pacific, are within the Phyla Annelida (1 species), Bryozoa (12), Cnidaria (2), Echinodermata (1), and Mollusca (8). When considering warmer regions, such as the Hawai'ian Islands, there are also 25 species not yet reported from the Central Indo-Pacific, 10 of which are distinct from the 25 species not yet present in the northeast Pacific. However, only one of those species has a documented native range that extends into tropical waters, the Cnidarian *Halecium tenellum*.

Introduction

In the six years since the devastating Great 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 have documented the arrival of over 650 debris items. Debris items include 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. Although identification and genetic verification is ongoing, there are nearly 380 taxa that have been collected on JTMD that landed in North American and the Hawai'ian Archipelago since 2012. 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; Lo et al. 2012; Clarke Murray 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 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.


Photo credit: Travis Haring (WDFW)

As of January 2017, only one JTMD species, the striped beakfish *Oplegnathus fasciatus*, has 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 risks associated with 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 to evaluating potential risks associated with JTMD species, we have a unique opportunity to examine those species that arrived on JTMD in greater detail in order to (1) increase our understanding of transoceanic dispersal of coastal species; and (2) advance one of the least understood aspects of invasion ecology – why some species are successfully transported to novel habitats outside of their current biogeographic range when others are not? The work contributes to the synthesis goals of the ADRIFT (Assessing the Debris-Related Impact From 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. Here, 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.

Methods

Database development and modification

We began our efforts using the PICES JTMD life history database available in spring 2016. We updated the JTMD species list until approximately May 2016, at which time we needed to finalize the species list for analysis. In January 2017, we removed a small number of species and updated nomenclature based on the most current JTMD species list from Dr. James Carlton. Therefore, our final database includes 135 species (Appendix 12.1).

Given that any robust statistical comparison among the JTMD species requires complete, or nearly complete, coverage across attributes, we took the following steps to modify the database. First, we incorporated cited and verified information presented by Dr. Michio Otani. Second, we added Phylum, Class, Order, and Family to the database. Third, we filled in some missing dropdown or multi-select fields based on information available in the "See Details" field, when deemed appropriate. Select information on congenerics was used to fill in some fields. Finally, we generated four categories for invasion history. These categories are:

1. **Yes = clear invasion history outside of native range**, with clearly documented establishment in non-native areas
2. **No = not found outside of native range**
3. **Cryptogenic = species with unknown origin**, meaning their native range is unclear (even if they were introduced via human-mediated transport, there is no way to know if the region of introduction was non-native or a reintroduction to their native region)
4. **Unclear = species with 'unclear establishment'**, meaning the species was introduced to a region outside their native range (via human-mediated transport) but has not established or was not documented since that first introduction event.

To validate these invasion history categories, we consulted the database, western and Japanese literature sources, and completed some further literature review to ensure we incorporated the most current information. Additionally, in late April - early May 2016, the categorization was compared with the global invasion status of JTMD species in the NEMESIS database (compiled by Paul Fofonoff, SERC). A final consultation with Drs. Jim Carlton and Greg Ruiz resulted in the categorization presented in the modified database.

Finally, variables that were included in the statistical analyses, hereafter referred to as "attributes", were transformed into binary or numerical data. For example, a species could be present in 8 of the 20 geographic regions. Therefore, there could be too many potential combinations for clear interpretation. Therefore, we included all "Realms" and "Regions" in the database with a binary entry system for each species. For each species, there would be a "0" if the species was not present in a particular "Realm" and "1" if it was present. For attributes with less than 10 possible combinations, such as "Reproductive Mode", we developed a numerical classification (1 = gonochoristic/dioecious, 2 = hermaphrodite/monoecious). Therefore, the final database had 100 fields, which often included multiple fields per attribute. For example, there are 12 Realms so we refer to "Realm" as the attribute and the actual Realms 1 through 12 as the database fields.

Specific changes that may be of particular interest are presented in further detail below. Many of the fields were developed based on the PICES Nonindigenous Species Information System (Lee & Reusser 2012) that was a product of PICES WG 21.

1) Within the attribute "Vector," the categories Infrastructure Development, Research and Education, Aquarium and Plant trade, and Habitat Restoration and Mitigation were never used so were removed. Only two species fell under the vector category Live Seafood (namely *Asterias amurensis* and *Didemnum vexillum*) so Live Seafood was not used as a vector in the analysis. The categories Hull fouling (recreational), Hull fouling (commercial), and Hull fouling (not specified) were combined into one broad hull fouling category, as we didn't need the distinction between commercial and recreational hull fouling for the purposes of this analysis.

2) Within the attribute "Temperature", the category Mild temperate was removed. Without guidelines for the temperature regimes, most species were filled out as "See Details." In order to translate the temperature information contained within the details tab to temperature categories, we used temperature intervals shown to be critical for marine biota, based on Payne et al. (2012). Cold temperate should never rise above 20˚C, and warm temperate should never fall below 12˚C (Payne et al. 2012). We found the mild temperate category arbitrary, as it could be either cool temperate or warm temperate as well, and found it hard to decipher between the two, so it was removed.

3) Within the attribute "Depth Regime", the category Coastal Fringe was used only once to describe *Telmatogeton japonicus*, so it was removed. The categories Upper Intertidal, Middle Intertidal, and Lower Intertidal were combined to form one category Intertidal. Bathyal, Hadal, and Abyssal were combined into one category Bathyal, which now encompasses all depths greater than 200 m. The categories Surface Epipelagic, Shallow Epipelagic, Deep Epipelagic, Mesopelagic, Bathypelagic, Abyssopelagic, and Hadopelagic were never used and were removed.

4) Within the attribute "Ecosystem", Rocky Intertidal and Rocky Subtidal were combined into one category Rocky, as the distinction between the environment above and below the low tide mark is already covered by Depth Regime. The categories Oyster/mussel Reef, Worm Reef, and Coralline Algae Reef were combined into one category Temperate Reef because all are found in temperate, cooler environments. Coral Reef was kept distinct as it is correlated with warmer, tropical environments.


Photo credit: Lightspeed Digital

5) For the attribute “Habitat”, the categories Epibenthic, Epiphytic, and Epizoic were combined into one category "Epibenthic”. The categories Semi-Infaunal and Infaunal were combined to simply Infaunal.

6) For the attribute “Substrate”, the categories Gravel, Cobble, and Rock were combined to simply Rock.

7) At this point, there were still a high number of “Not Found” entries. Therefore, we relied on qualitative data from Dr. Michio Otani, appropriate related species information contained within the details tab, additional review of select literature, and a logical rationale. Certain changes were made for species without further information or related species information. For example, few higher-level eukaryote coastal invertebrate species are asexually reproducing, so the default for a species without that information available is that it does not reproduce asexually.

8) The database at this stage had 135 species, 20 attributes, and 135 fields. Any attributes or species that still had poor coverage were removed for quantitative analysis. The following data-poor attributes were removed: salinity regime reproductive, temperature regime reproductive, secondary vector, maturity size, maturity age, broods per year, fecundity, egg size, longevity, and forage mode. The following data poor species, all with less than 65% data coverage, were also removed: *Tectura emydia, Hippothoa imperforata, Placiphorella stimpsoni, Bankia bipennata, Havelockia versicolor, Arabella semimaculata, Hydrodendron gracile, Gromia oviformis*. *Cibicides lobatulus* was also depleted on account of taxonomic dissimilarity (the reproductive categories in this JTMD invertebrate database didn’t make sense for the type of reproduction performed by *C. lobatulus*). The final database for quantitative analysis included 126 species (Appendix 12.1) with 16 attributes and 100 fields (Appendix 12.2). There were four additional attributes for species with known invasion history (Non-native Realm, Non-native Region, Non-native Temperature, and Non-native Salinity) and 132 fields (Appendix 12.2).

Photo credit: Ocean Legacy

Qualitative synthesis

We compiled summaries of JTMD species across various categories of interest, such as Phyla or invasion history, to provide some synthesis of the attributes of all 135 species in the database. The number of species examined depended on the coverage across attributes. We had good coverage on 135 species and include a qualitative synthesis of those species. We had over 95% coverage for 126 species, which were used in the quantitative analysis described below.

Quantitative analysis

Nonmetric Multidimensional Scaling (NMS) was used to ordinate species in multi-dimensional space. 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 1999). JTMD species with adequate information (n = 126) and 16 attributes were included in the initial analysis. A measure of 'stress', which 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, was determined. Pearson correlation analysis was used to examine the relationships between NMS axis scores and variables (distributional, environmental, and life history attributes) included in the analysis, which provides information on which attributes account for separation along axes. Significance levels for the correlation analyses were corrected for multiple comparisons using the Bonferroni correction. PC-ORD Version 7 was used for NMS analyses (McCune and Mefford 1999).

Initially we compared all species with adequate coverage across variables (n = 126), which included all four invasion history categories (cryptogenic, unclear, invasion history, no invasion history). We chose to analyze the species matrix in two ways. First, we used only the geographic distribution information (Realm and Region). Second, we used only the environmental and life history attributes. We adopted this approach because it is expected that 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 we were also interested in the similarities in environmental and life history attributes independent of geographic distribution, we decided to complete both analyses for comparison.

We also wanted to determine if there were significant differences in attributes among species groups with different invasion histories. Therefore, we completed a Multi-Response Permutation Procedure (MRPP), which estimates a weighted mean within-group distance (δ) to determine the probability of the observed δ compared with δ generated with random clusters. We completed two analyses, one including species categorized as cryptogenic, known invasion history, and no known invasion history (n = 126) and the other with only those species with and without invasion history (n = 103). The six species with unclear establishment were removed from both analyses due to their low number and ambiguous status.

We completed Indicator "Species" Analysis (ISA) on the species x attribute matrices to determine which attributes were statistically significant indicators of each group (cryptogenic, invasion history, and no invasion history). An ISA combines information on relative abundance and frequency of occurrence to identify attributes that are most characteristic of each group. In this analysis, certain attributes, such as “Developmental Mode” could be indicators of group separation, which means that there are statistically different frequencies of occurrence of planktonic developers in one group compared to another. Statistical significance was determined based on Monte Carlo tests with 5000 permutations for comparison with observed Indicator Values. Analyses were completed using PC-ORD 7.0.

Finally, to further explore attributes only of JTMD species with known invasion histories, we completed two additional ordinations, one with only geographic distribution information (Realm, Nonnative Realm, Region, and Nonnative Region) and the other with only environmental and life history attributes. Our aim was to evaluate patterns and highlight differences among this group of species (n = 31), which are of particular interest in terms of risk evaluation.

Results

Qualitative synthesis

The 135 JTMD species included in the database represent 12 phyla, with Mollusca, Crustacea, and Bryozoa each contributing slightly over 20% of the total (Figure 12-1). Four phyla (Foraminifera, Chordata, Cercozoa, and Sipuncula) were each represented by one species. As noted, a species had to have broad coverage across attributes for inclusion in the final database. This was the only criterion as there was no systematic selection of species for analysis. However, it should be noted that taxa had to be identified to species (or rarely a species complex, such as *Jassa marmorata* complex) with a high level of confidence for inclusion. Therefore, there is likely some biased representation based on ease of identification, prior knowledge of taxa, and somewhat uneven taxonomic effort across phyla. However, we consider the 135 species to be a representative subset of the biota that have been documented on JTMD.

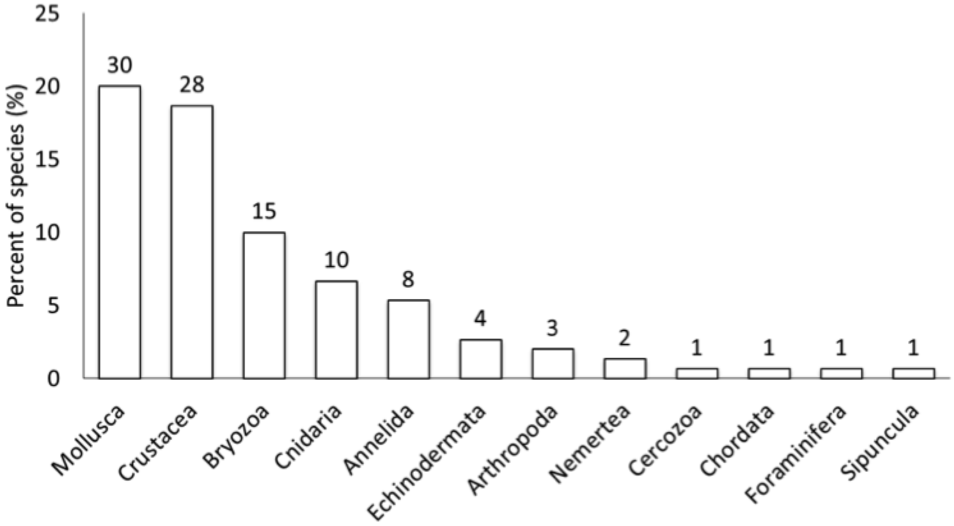

Figure 12-1. The percent of JTMD species per phyla (n = 104 species). The number of species per phyla is given above each bar.

The reported native realm for these 135 JTMD species covers the globe (Figure 12-2) with species ranging from the Southern Ocean (hydrozoan *Obelia longissima*) to the Arctic (amphipod *Ampithoe lacertosa*). However, the majority are native to the northwest Pacific, followed by northeast Pacific, and the Central Indo-Pacific (Figure 12-3). Given that our aim was to summarize key attributes of JTMD species and then compare those attributes across groups with different prior invasion histories, an initial step was to categorize each species by invasion history. The majority of species had no invasion history (>50% of the total), while the remainder had a documented invasion history (23%), an introduction but unclear establishment (4%), or were cryptogenic (unknown origin) (14%) (Table 12-1). Hence, most of the JTMD species have no invasion history. However, many of the species have documented transport vectors and, as JTMD is arguably a newly documented species transport vector, we wanted to determine the prior transport history for each species (Figure 12-3). Eight transport categories were documented, and the greatest number of species (40) was reported as hull fouling, followed by transportation through aquaculture and fisheries activities, and ballast water (Figure 12-4).

Estimates of the number of propagules (or individuals) entering a new area are needed to generate a meaningful estimate of propagule pressure, which in at least some instances has been correlated with likelihood of successful establishment (Lockwood et al. 2005; Lo et al. 2012; Capinha et al. 2013). The literature review included an estimate of abundance in native, and when applicable, non-native, habitats. However, the vast majority of species (>90) had at least one citation that reported the species to be "common". Additionally, a relatively large number of species (n = 40) were reported to be abundant or common as well as few or rare, likely highlighting the spatial and temporal variation in abundance. Thus, given the difficulty in assigning a valid estimate of natural abundance and the potential mismatch between native abundance and actual abundance on JTMD, we did not include the attribute “Abundance” in the quantitative analysis.

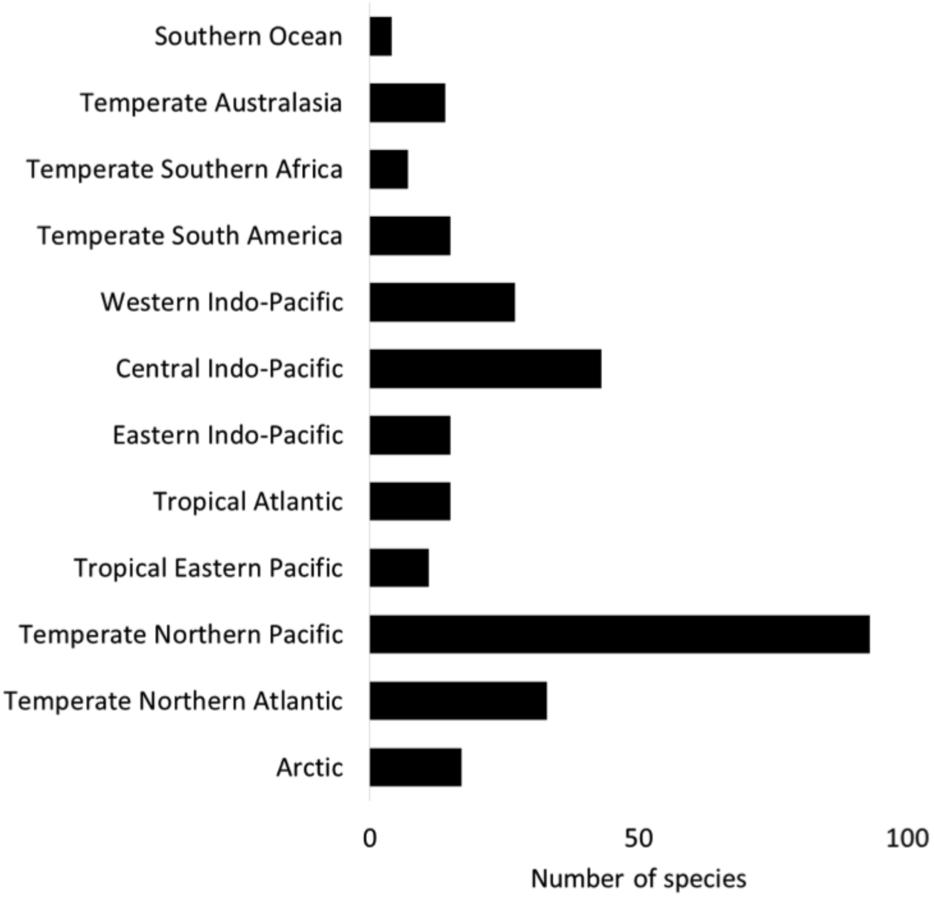

Figure 12-2. The reported native realm of origin for 104 JTMD species. The number of species per realm is reported and species can be present in multiple realms. The realms are ordered geographically from the south to north.

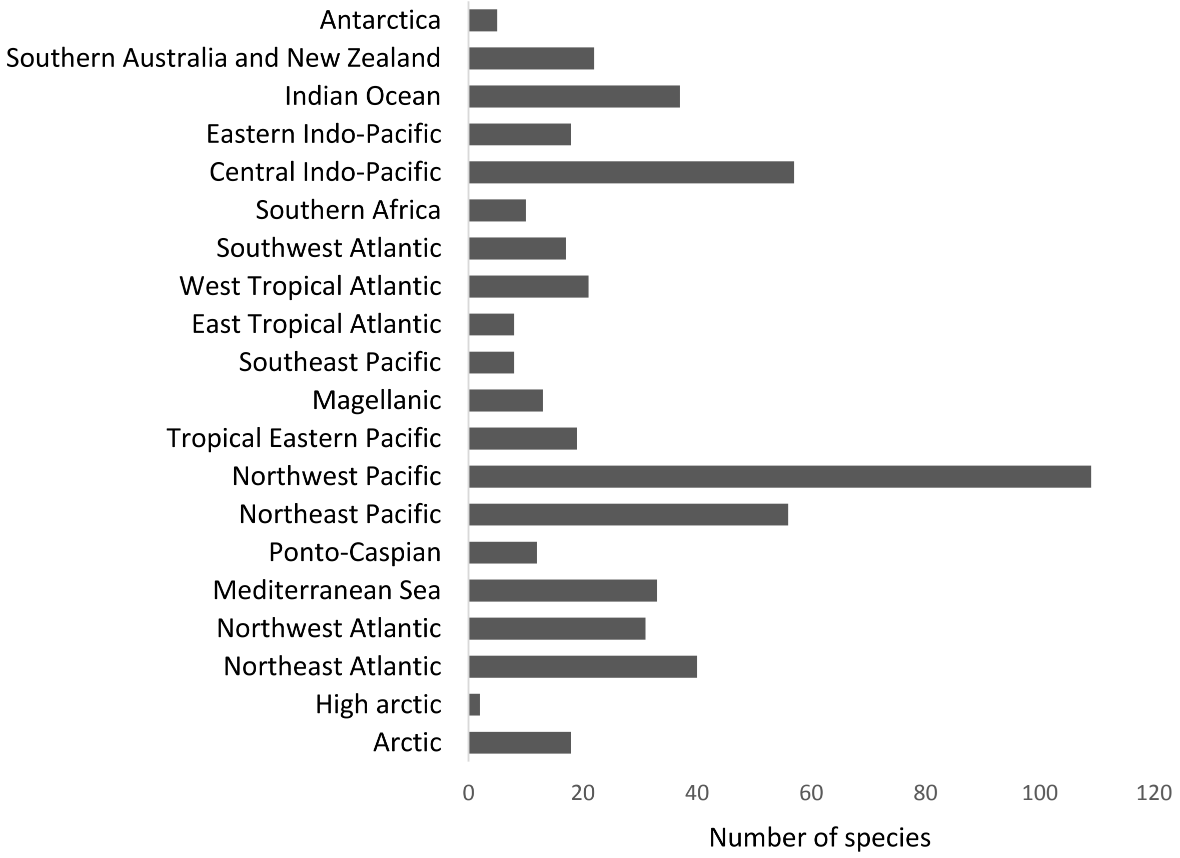

Figure 12-3. The native regions for 135 JTMD species, based on the Marine Ecoregions of the World. Number of species found per region is shown, and species can fall under multiple regions if applicable. Regions are ordered from south to north.

Table 12-1. The number and percent of JTMD species within each invasion category (total n = 104).

Invasion History	**Number of species**	**Percentage of species**
No invasion history	69	66.3
Known invasion history	31	29.8
Cryptogenic - unknown origin	4	3.8

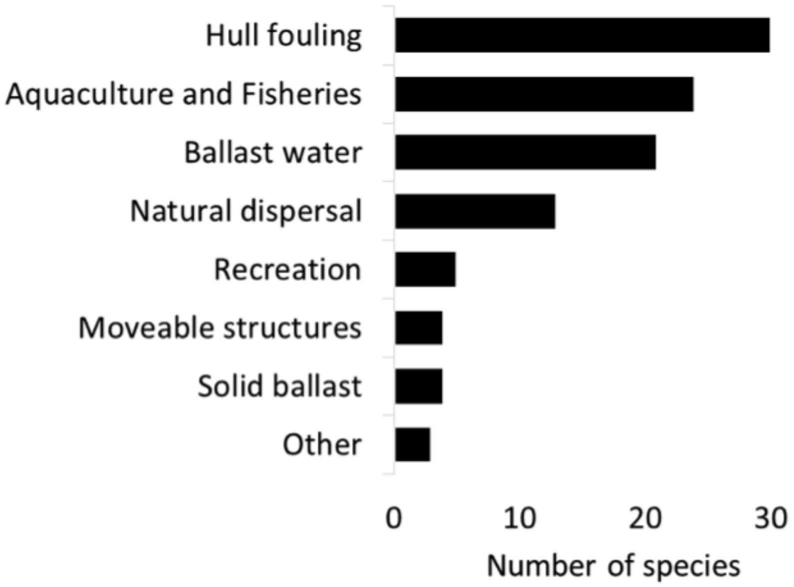

Figure 12-4. The number of JTMD species documented per transport vector; each species can be reported under multiple vectors. A total of 45 species of 104 total have been documented on a vector, including 30 of the 31 species with known invasion history, 3 of the 4 cryptogenic species, and 12 that were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

Quantitative analysis

We present the results of analyses based on the 126 species that comprised three of the invasion categories: cryptogenic, known invasion history, and no invasion history. Given that there were only 5 species with unclear invasion history and the results were similar with or without these species, we removed them to facilitate comparison among the remaining species.

Geographic distribution among invasion histories

The variability among the 126 species was well-described with a two-dimensional ordination that accounted for 79% of the variation among the species' geographic distributions (stress = 12.2, 55 iterations). Axis 1 accounted for 55% of the variation among species and Axis 2 for 33% of the variation. The greatest separation was between species from the Western Indo-Pacific and those from the Temperate North Pacific. While the geographic distribution of cryptogenic species was statistically distinct from species with and without any invasion history (MRPP pairwise comparisons $P < 0.001$), there was no difference between species with and without invasion history ($P = 0.36$). Cryptogenic species had greater representation in the Arctic, Temperate and Tropical North Atlantic, and Southern Australia and New Zealand.

Environmental and life history attributes across invasion histories

The ordination of the 126 species based only on environmental and life history attributes also accounted for a high level of variation (79%) (stress = 16.7, 94 iterations). Axis 1 accounted for 42% of the variation and separated species primarily on feeding, reproduction, and developmental mode along with native temperature regimes and habitats (Figure 12-5). Axis 2 accounted for 21% of the variation in the data and separated species primarily on salinity tolerance, substrate, and developmental mode. Axis 3 accounted for 17% of the total variation and separated species primarily on differences in native temperature (Table 12-2).

There was some separation between species with and without invasion histories and cryptogenic species (MRPP $P < 0.001$). However, as a group, cryptogenic species were more similar to those with invasion history ($P = 0.08$). The indicator analysis demonstrated that cryptogenic species were characterized by a greater representation in cold and cool waters as well as either deeper, water column habitats or coastal shores associated with vegetation. Species with known invasion history were distinguished by a greater representation on temperate reefs, more fouling species, and more species found on hardpan and artificial substrates.

Given the ambiguity associated with cryptogenic species and their statistical distinction, we also completed an ordination using only species with and without invasion histories (Figure 12-6). The ordination of the 103 species with and without known invasion history based on environmental and life history attributes accounted for a similarly high level of variation (72%) (stress = 17, 69 iterations). Similar to the analysis that included cryptogenic species, Axis 1 accounted for 39% of the variation and separated species based on feeding, reproduction, and developmental mode and native temperature regime (Figure 12-6). Axis 2 accounted for 18% of the variation in the data and separated species primarily on salinity tolerance, habitat, and developmental mode. Axis 3 accounted for 15% of the total variation and separated largely based on temperature.

There was also a significant statistical separation between species with and without invasion histories (MRPP, $P < 0.001$). Based on the indicator analysis, species with documented invasion history were distinguished by a greater occurrence on temperate reef habitat and artificial and hardpan substrates as well as a greater representation of fouling organisms. Species with documented invasion history were also more commonly present in subtropical and tropical waters and more protected habitats and they exhibited greater salinity tolerance. Asexual reproduction was moderately, but significantly, less common in species with documented invasion history.

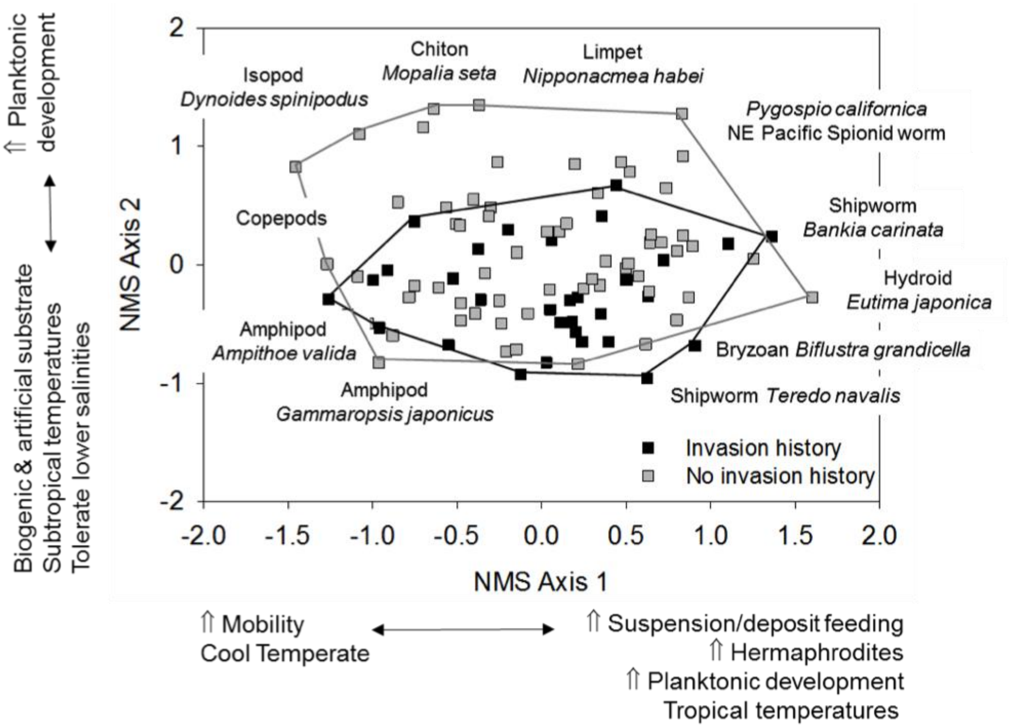

Figure 12-5. Ordination of 94 JTMD species with known or no invasion history based only on life history and ecological attributes. Attributes significantly correlated with axis scores are included along each axis. See Table 12-2 for additional details on the correlation analysis. The species at the outer boundaries (joined lines) of the multivariate ordination are identified for reference.

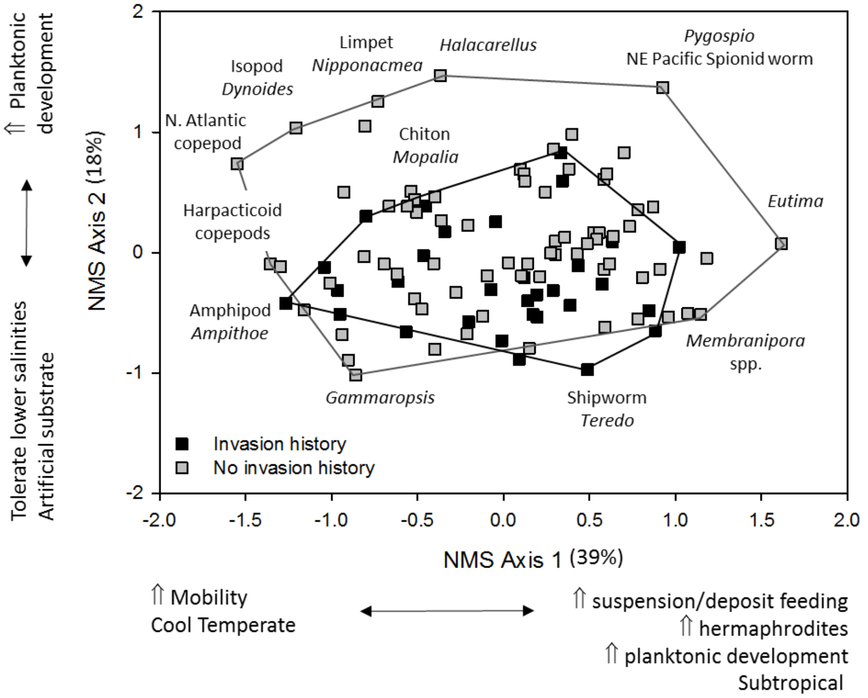

Figure 12-6. Ordination of 103 JTMD species with known invasion history. Attributes significantly correlated with axis scores are included. See Table 12-3 for additional details on the correlation analysis.

Table 12-2. Correlations between axis scores from the Nonmetric Multidimensional Scaling ordinations and the JTMD species attributes included in the analysis. Ordination included 126 species that could be identified as cryptogenic, known invasion history, or no invasion history. Only correlations that are significant after correction for multiple comparisons (r > 0.350) are included. See Appendix 12.2 for attribute details.

Attributes	Axis 1	Attributes	Axis 2	Attributes	Axis 3
Trophic (⇑ suspension & deposit feeding)	0.807	Development (direct ⇒ planktonic)	0.369	Subtropical	0.768
Reproduction (gonochoristic ⇒ hermaphroditic)	0.529	Submerged aquatic veg.	-0.354	Tropical	0.540
Development (direct ⇒ planktonic)	0.484	Reproduction (sexual ⇒ asexual)	-0.375	Coral reef	0.383
Asexual Reproduction (sexual ⇒ asexual)	0.398	Cool temperate	-0.386	Cool temperate	-0.363
Tropical	0.390	Oligohaline	-0.411		
Subtropical	0.377	Flotsam	-0.423		
Macroalgae beds	-0.358	Fouling	-0.465		
Kelp forests	-0.355	Temperate reef	-0.466		
Rocky ecosystems	-0.332	Artificial substrate	-0.515		
Mud substrate	-0.392	Biogenic	-0.542		
Cold water	-0.337	Polyhaline (18 to >30)	-0.552		
Infaunal	-0.451	Mesohaline (5 to <18)	-0.581		
Tidal flat ecosystems	-0.470				
Cool temperate	-0.808				

Table 12-3. Correlations between Axis 1, 2, and 3 scores from the Nonmetric Multidimensional Scaling ordinations and the JTMD species attributes included in the analysis. Ordination included 94 species that could be identified as having a known invasion history or no invasion history. Only correlations that were significant after correction for multiple comparisons (r > 0.350) are included. The attribute "Development" is included for Axis 2 as it was the only marginally significant positive correlate. See Appendix 12.2 for attribute details.

Attributes	Axis 1	Attributes	Axis 2	Attributes	Axis 3
Trophic (⇑ suspension & deposit feeding)	0.801	Development (direct ⇒ planktonic)	0.326*	Subtropical	0.683
Tropical	0.463	Temperate reef	-0.386	Tropical	0.676
Reproduction (gonochoristic ⇒ hermaphroditic)	0.461	Polyhaline (18 to >30)	-0.520	Coral reef	0.367
Development (direct ⇒ planktonic)	0.438	Mesohaline (5 to <18)	-0.561	Asexual Reproduction (sexual ⇒ asexual)	-0.518
Asexual Reproduction (sexual ⇒ asexual)	0.403	Artificial substrate	-0.568	Cool temperate	-0.367
Subtropical	0.387	Fouling	-0.576		
Infaunal	-0.359	Subtropical	-0.590		
Tide flat ecosystems	-0.430	Warm temperate	-0.606		
Macroalgae beds	-0.483	Biogenic	-0.618		
Cold water	-0.377				
Rocky ecosystems	-0.382				
Cool temperate	-0.544				
Mobility	-0.787				

Discussion

The ability to predict biological invasions remains notoriously challenging (Kolar & Lodge 2002; Romanuk et al. 2009). Although various predictors appear promising in a particular taxonomic group or scenario, there is often minimal success when more broadly applied. Related efforts have sought to identify life history traits associated with successful invaders. Such an approach can be used to evaluate relevant hypotheses, such as whether or not successful invaders have higher reproductive rates (Sol et al. 2012). Our focus was to synthesize key attributes within the JTMD species pool, identify those attributes that account for the variation within the JTMD species pool, and highlight those attributes that vary between JTMD species with and without known invasion histories. Theoretically, the outcome of such efforts can help focus management and monitoring activities.

Based on geographic distribution alone, there was substantial structuring of the JTMD species and cryptogenic species were distinct from those with and without invasion history. Not surprisingly, cryptogenic species had a broader geographic representation. However, when analyzed with the environmental and life history attributes, we also documented a substantial amount of group separation within the JTMD species pool. It is interesting that life history attributes accounted for much of the separation among species, including trophic status, reproductive mode, and development mode.

Given the focus on risk assessment and the need to evaluate the likelihood of a negative outcome associated with any of the JTMD species becoming established outside their native ranges, the direct comparison of JTMD species with and without invasion histories is the most relevant. We documented statistically significant differences between species with and without known invasion histories. Species with known invasion history were more commonly present in (but not necessarily limited to) sub-tropical and tropical areas, more protected habitats, and exhibited greater salinity tolerance. Given the statistical distinction between JTMD species with and without invasion history, we can compare the species with no known invasion history that are most closely located in three-dimensional space to the statistically distinct group of species with known invasion histories. Such an approach allows us to ask the question “which species have similar attributes?” For example, the multivariate analysis decomposes the species x attribute database into three axes of variation and each species is essentially assigned a position in three-dimensional space (i.e., an x-, y-, and z-value). We can then identify the JTMD species with no known invasion history that are most similar to those with prior invasion histories. This approach identified 45 JTMD species with no known invasion history from the Phyla Annelida, Bryozoa, Crustacea, Cnidaria, Echinodermata, Mollusca, and Nemertea that were within the same coordinate space as JTMD species with known invasion history. However, 20 of those species are already reported to occur in the northeast Pacific, leaving 25 species from the Phyla Annelida (1), Bryozoa (12), Cnidaria (2), Echinodermata (1), and Mollusca (8) that are most similar to JTMD species with invasion histories but not yet established in the northeast Pacific. When considering warmer regions that received large amounts of JTMD, such as the Hawai'ian Islands, there are also 25 species not yet reported from the Central Indo-Pacific, 10 of which are distinct from the 25 species not yet present in the northeast Pacific. However, only one of those species has a documented native range that extends into tropical waters, the Cnidarian *Halecium tenellum*.


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Overall, the database development and related analyses provide a qualitative and quantitative synthesis of the JTMD biota that contributes to both basic understanding of species’ ocean transport and invasion ecology. While JTMD species known to have established outside their native ranges are clearly of concern, particularly in geographic areas where they have not yet established, the analyses presented here may be able to highlight species with similar attributes that may be of concern in Pacific North America and Hawaii. Our efforts can complement other approaches to identifying species of concern (see chapter 15).

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Appendices

Appendix 12.1. List of 135 species included in distributional, environmental, and life history database of Japanese Tsunami Marine Species

Appendix 12.2. Attribute name and associated field values for all Japan Tsunami Marine Species included in the database

Appendix 12-1. List of 135 species included in distributional, environmental, and life history database of Japanese Tsunami Marine Species

List of 135 species included in distributional, environmental, and life history database of Japanese Tsunami Marine Species. Species in bold were included in the qualitative synthesis but not the quantitative analysis due to missing information.

Species	Invasion Category
Aetea anguina	Cryptogenic
Aetea truncate	Cryptogenic
Amblyosyllis speciosa	Known invasion history
Amphisbetia furcate	No known invasion history
Ampithoe lacertosa	Cryptogenic
Ampithoe valida	Known invasion history
Anomia cytaeum	No known invasion history
Aphelasterias japonica	No known invasion history
Arabella semimaculata	No known invasion history
Arbocuspis bellula	No known invasion history
Arbopercula angulate	Cryptogenic
Arca boucardi	No known invasion history
Arca navicularis	No known invasion history
Asterias amurensis	Known invasion history
Balanus crenatus	No known invasion history
Balanus glandula	Known invasion history
Balanus trigonus	Known invasion history
Bankia carinata	Cryptogenic
Bankia bipennata	Unclear
Biflustra grandicella	Known invasion history
Biflustra irregulata	No known invasion history
Bougainvillia muscus	Cryptogenic
Callopora craticula	No known invasion history
Caprella mutica	Known invasion history
Caprella penantis	Cryptogenic
Celleporella hyalina	No known invasion history
Celleporina nordenskjoldi	No known invasion history
Celleporina porosissima	No known invasion history
Celleporina umbonata	No known invasion history
Chthamalus challenger	Known invasion history

Cibicides lobatulus	No known invasion history
Crassostrea gigas	Known invasion history
Crepidula onyx	Known invasion history
Cryptosula pallasiana	Known invasion history
Dactylopodamphiascopsis latifolius	No known invasion history
Dendostrea folium	Known invasion history
Dendronotus frondosus	No known invasion history
Diadumene lineata	Known invasion history
Didemnum vexillum	Known invasion history
Dolabella auricularia	No known invasion history
Dynoides spinipodus	No known invasion history
Endeis nodosa	Known invasion history
Entodesma navicula	No known invasion history
Escharella hozawai	No known invasion history
Eulalia quadrioculata	No known invasion history
Eutima japonica	No known invasion history
Exochella tricuspis	No known invasion history
Gammaropsis japonicas	No known invasion history
Gromia oviformis	Cryptogenic
Halacarellus schefferi	No known invasion history
Halecium tenellum	No known invasion history
Halosydna brevisetosa	No known invasion history
Harmothoe imbricata	Cryptogenic
Harpacticus nicacensis	No known invasion history
Harpacticus pacificus	No known invasion history
Harpacticus septentrionalis	No known invasion history
Havelockia versicolor	No known invasion history
Hemigrapsus sanguineus	Known invasion history
Hermissenda crassicornis	No known invasion history
Heterolaophonte discophora	No known invasion history
Hiatella orientalis	Known invasion history
Hippothoa imperforata	No known invasion history
Hydrodendron gracile	No known invasion history
Hydroides ezoensis	Known invasion history
Hyotissa numisma	Unclear
Ianiropsis serricaudis	Known invasion history
Jassa marmorata complex	Known invasion history
Laevichlamys irregularis	No known invasion history

Limaria hakodatensis	No known invasion history
Lyrodus takanoshimensis	Known invasion history
Megabalanus rosa	Known invasion history
Megabalanus zebra	Known invasion history
Membranipora conjunctiva	No known invasion history
Membranipora raymondi	No known invasion history
Membranipora serrilamella	No known invasion history
Membraniporopsis serrilamelloides	No known invasion history
Metridium dianthus	Cryptogenic
Microporella borealis	No known invasion history
Microporella pulchra	No known invasion history
Mitrella moleculina	No known invasion history
Modiolus nipponicus	No known invasion history
Mopalia seta	No known invasion history
Musculus cupreus	No known invasion history
Mytilisepta yessoensis	Unclear
Mytilus coruscus	No known invasion history
Mytilus galloprovincialis	Known invasion history
Mytilus trossulus	No known invasion history
Nereis pelagica	Cryptogenic
Nipponacmea habei	No known invasion history
Obelia griffin	Cryptogenic
Obelia longissima	Cryptogenic
Oedignathus inermis	No known invasion history
Oerstedia dorsalis	No known invasion history
Orthopyxis caliculata	Cryptogenic
Orthopyxis platycarpa	No known invasion history
Pacificincola perforata	Unclear
Paralaophonte congenera	No known invasion history
Paramphiascella fulvofasciata	Cryptogenic
Parastenhelia spinosa	No known invasion history
Parathalestris intermedia	No known invasion history
Pascahinnites coruscans	No known invasion history
Patiria pectinifera	No known invasion history
Perinereis nigropunctata	No known invasion history
Phascolosoma scolops	Known invasion history
Placiphorella stimpsoni	No known invasion history
Plumularia setacea	Cryptogenic

Pocillopora damicornis	No known invasion history
Pseudoctomeris sulcata	No known invasion history
Pygospio californica	No known invasion history
Sarsamphiascus minutus	No known invasion history
Scaeochlamys squamata	No known invasion history
Schizoporella japonica	Known invasion history
Semibalanus cariosus	No known invasion history
Septifer virgatus	No known invasion history
Sertularella mutsuensis	No known invasion history
Smittoidea spinigera	No known invasion history
Sphaerozius nitidus	Unclear
Spirobranchus polytrema	Unclear
Stenothoe crenulata	Known invasion history
Syllis elongate	No known invasion history
Syllis hyaline	Cryptogenic
Tectura emydia	No known invasion history
Telmatogeton japonicus	Known invasion history
Temnotrema sculptum	No known invasion history
Teredo navalis	Known invasion history
Teredothyra smithi	No known invasion history
Tetrastemma nigrifrons	No known invasion history
Tricellaria inopinata	Known invasion history
Trypanosyllis zebra	No known invasion history
Tubulipora masakiensis	No known invasion history
Tubulipora pulchra	No known invasion history
Walkeria uva	Cryptogenic
Watersipora mawatarii	No known invasion history
Watersipora subatra	Known invasion history
Zeuxo normani	Cryptogenic

Appendix 12-2. Attribute name and associated field values for all Japan Tsunami Marine Species included in the database

Attribute	Definition
Realm (Native and Non-native)	
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
Region (Native and Non-native)	
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
Temperature regime (Native and Non-native)	
Temp_1	Cold water
Temp_2	Cool temperate
Temp_3	Warm temperate

Temp_4	Subtropical
Temp_5	Tropical
Salinity regime (Native and Non-native)	
Sal_1	Freshwater = <0.5
Sal_2	Oligohaline = 0.5 - <5
Sal_3	Mesohaline = 5 - <18
Sal_4	Polyhaline = 18 - <30
Sal_5	Euhaline = 30 - <40
Sal_6	Hypersaline = ≥ 40
Fertilization mode	
1	Internal fertilization
2	External fertilization
Reproductive mode	
1	Gonochoristic/dioecious
2	Hermaphrodite/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	Lecithothrophic, and planktotrophic (*Dendronotus fronfosus* only)
Asexual reproduction	
1	Does not reproduce asexually
2	Binary fission Splitting into two approximately equal parts
3	Budding/fragmentation: splitting into unequal parts. Buds may form on the body of the “parent”
4	Parthenogenesis: the development of an unfertilized egg in animals.
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 - 30m
Depth_4	Deep subtidal = >30 - 200m
Depth_5	Bathyal = >200

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
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

Exposure	
Exp	Exposed
Semi_exp	Semi-exposed
Protect	Protected
V_protect	Very protected
Trophic status	
1	Herbivore
2	Omnivore
3	Predator
4	Detritivore
5	Suspension feeder
6	Deposit feeder
7	Herbivore, Suspension feeder
8	Suspension feeder, deposit feeder

THEME V – Detection of Invasion

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

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Abstract

The Great Tsunami of 2011 resulted in an unprecedented dispersal event of marine biota from Asian coastal waters to the 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 3 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 four-fold, underscoring the potential for high levels of hidden parasite diversity among the nearly 380 invertebrate taxa detected on JTMD to date, since none of these have been tested for parasite species richness.

Our extensive surveys of mussels and also fouling communities along Pacific 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 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 provide significant opportunity for invasions. Despite extensive analysis to date, the likelihood of detecting invasions during our project 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 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 current research aims to: 1) Detect new JTMD-associated invertebrate invasions to North American waters and 2) Design and implementation of 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

Survey of invertebrate communities in North America

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 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 13.7 x 13.7 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


Photo credit: JaNUS Co

coincide with the period of high seasonal recruitment and provide sufficient to develop mature communities (Ruiz et al. unpublished data).

Table 13-1. Sites of biofouling community surveys using standardized fouling panels. Bold indicates core sites with extensive surveys. Shown are states or province, location, total number of sites and panels per location.

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

In 2015, we collected and processed all panels at each of these sites, 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 SERC. All vouchers for molecular genetic analyses were sent to Moss Landing Marine Labs (MLML).

Our highest priorities 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 west coast, having only limited surveys to date for biofouling biota. 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 invasions that predate JTMD arrivals in North America 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 landing site and hotspot for JTMD species landings, such that measures here served both as baseline and detection effort. The dispersion of sample locations for these two sites is shown in Figure 13-1.

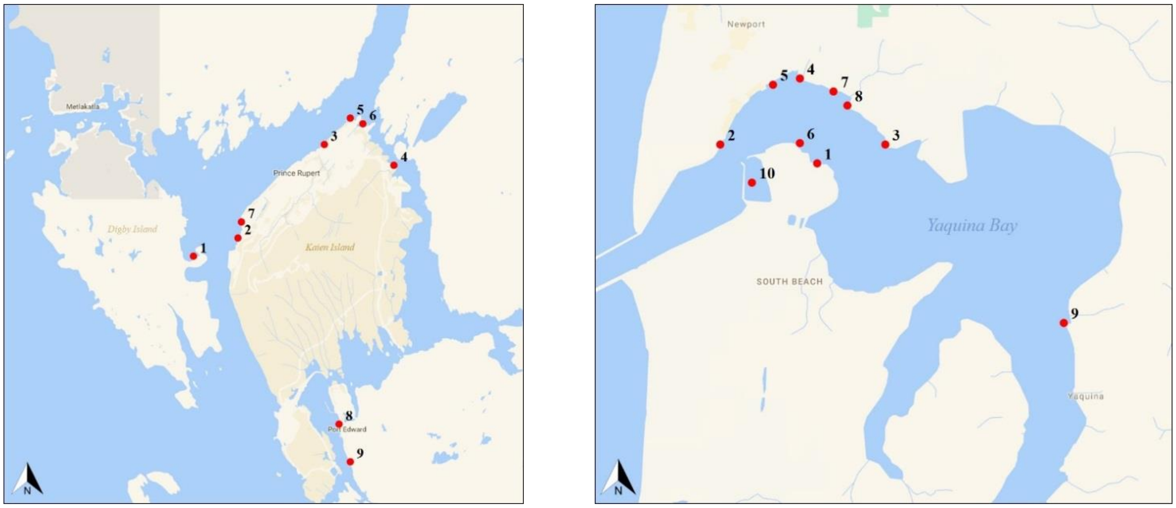

Figure 13-1 Sites of fouling panel surveys in Prince Rupert, BC (left) and Yaquina Bay, OR (right). Each site was surveyed with n=5 fouling panels.

The sites from WA 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 Year 3 (15 months after initial deployment), but we had significant losses during this time. Thus, samples from these bays are unfortunately not available, but this was also a very small number of intended sites (unlike Yaquina Bay or Prince Rupert, with 10 sites each), having low impact to the overall project results. We hope to conduct a future survey of these areas, but this is beyond the scope of the current project. In addition to the surveys conducted during the PICES/MoE ADRIFT program, we have conducted identical surveys in several other bays in California waters in the past five years. This provides further baseline data on resident species.

We worked intensively with colleagues in Hawaii to implement an identical biofouling survey to those along Pacific North America (above). We provided protocols and staff time to advance this work. In Year 2, we focused on Oahu, with panels deployed at 10 sites (100 panels total). These were retrieved and processed by SERC staff from December 6-18, 2015. The location of survey sites is shown in Figure 13-2. This survey generated a similar set of vouchers for morphological and genetic analyses to those in North America. Hawaii has funded independent taxonomists for identification of some vouchers, and SERC is continuing to provide assistance with data management and analysis.

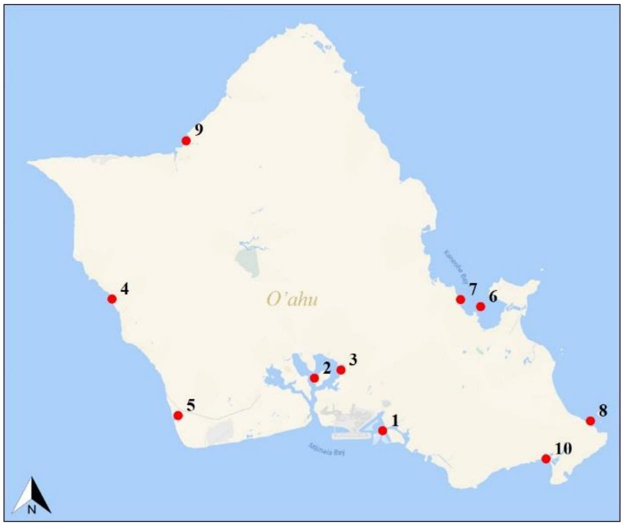

Figure 13-2. Sites of fouling panel surveys on Oahu, Hawaii. Each site was surveyed with n=5 fouling panels.

In western British Columbia, panels were deployed using similar methods at multiple sites in 2015 (Figure 13-4). Panels were deployed at ten sites in Prince Rupert (50 panels total), five sites in Tofino (20), four sites in Ucluelet (30), and five sites in Haida Gwaii (40). The Prince Rupert panels were retrieved from September 29 – October 8, 2015, the Haida Gwaii panels were retrieved from October 3 – November 3, 2015, and the Tofino and Ucluelet panels were retrieved from November 16-18, 2015. We developed joint protocols for standard photographs and a rapid assessment for target invertebrate species, and these panels were preserved for further potential subsequent analyses.

North American surveys for parasites

The parastitic 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, including our Canadian PICES colleagues. We obtained 4,087 mussels from Pacific North America for multiple analyses (Table 13-2). 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 described in Chapter 7. The mussel tissues were sent to MLML to be screened for Japanese mussel species.

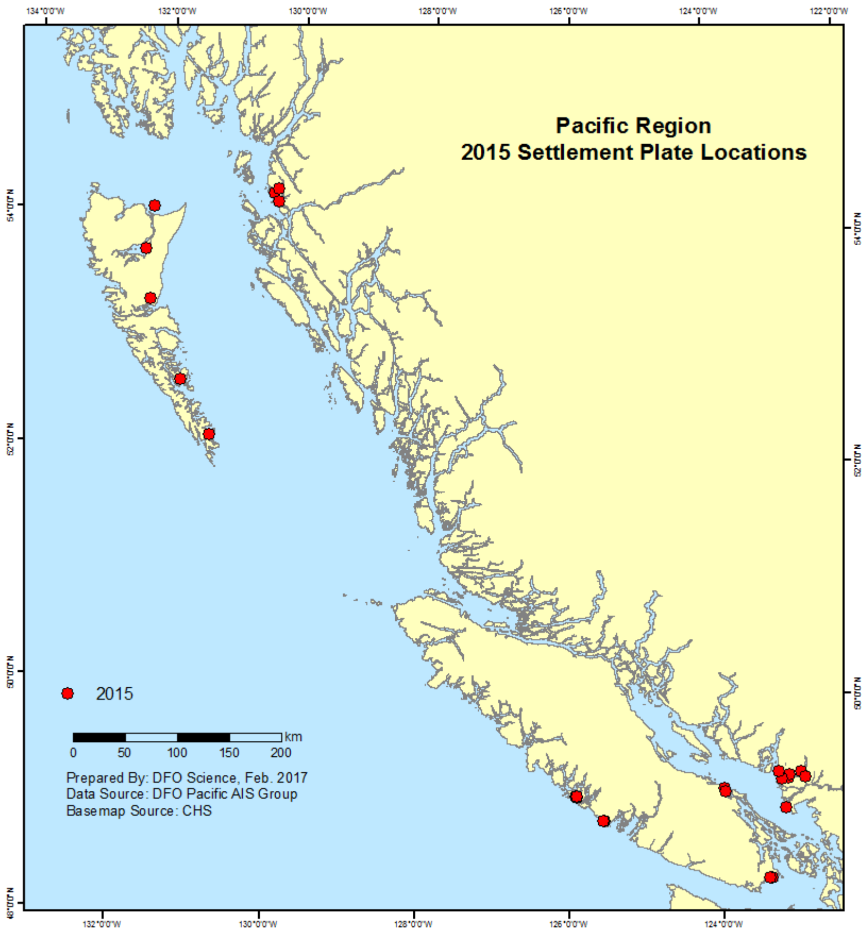

Figure 13-3. Sites of fouling panel surveys in British Columbia, Canada.

Table 13-2. Mussels collected for analyses of parasites and host genetics of resident populations in Pacific North America. Shown are year, site, total number of individuals/site, and number available for each analysis type.

Collection Year	State / Province	Bay 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)			**4087**	**3475**	**3229**	**3483**
		**Bay sampled twice				

Results

Surveys for invertebrates in North America

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 work in the PICES/MoE ADRIFT project focused primarily on five selected bays (Table 13-1), we have also conducted contemporary surveys in an additional eight bays along this same coast, allowing a much broader analysis of nonindigenous species (NIS) for Pacific North America. Across the thirteen bays, we have detected 27-71 total sessile invertebrate species per bay, including 8-27 NIS per bay (Figure 13-4). NIS represented from 5-44% 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 PICES/MoE 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, divided by 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 serve 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 potential JTMD invasions in the future (see Discussion).

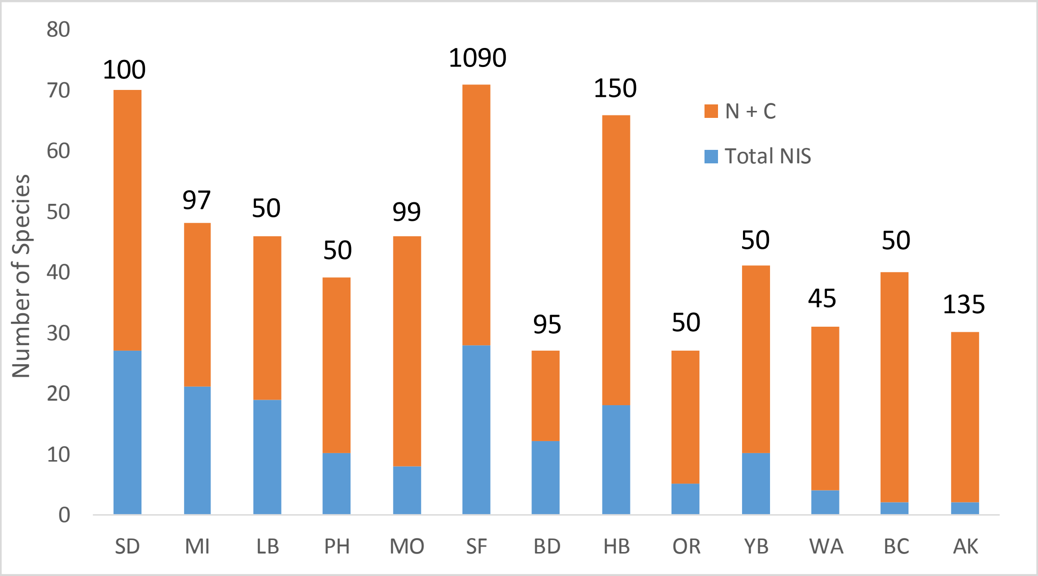

Figure 13-4 Total number of sessile invertebrate species detected per bay survey. The figure indicates the contribution of NIS versus all other taxa (N = Native, C = Cryptogenic). Number of panels surveyed per bay shown on top, and bay shown on x-axis includes (left to right): San Diego, CA (SD); Mission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

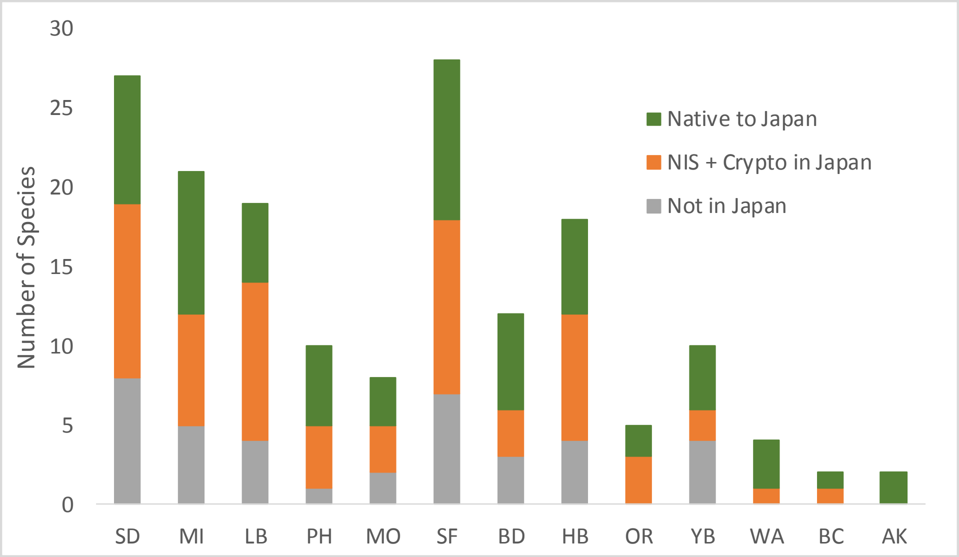

Figure 13-5. Total number of non-indigenous sessile invertebrates detected per bay survey. The figure indicates the number of species per bay that are considered (a) native to Japan, (b) occur in Japan as introduced (NIS) or cryptogenic, or (c) are not reported to occur in Japan. Bay shown on x-axis includes (left to right): San Diego, CA (SD); Mission Bay, CA (MI), Long Beach, CA (LB), Port Hueneme, CA (PH), Morro Bay, CA (MO); San Francisco Bay, CA (SF); Bodega Bay, CA (BD); Humboldt Bay, CA (HB); Coos Bay, OR (OR); Yaquina Bay, Oregon (YB); Puget Sound, WA (WA); Prince Rupert, BC (BC); Ketchikan, AK (AK). Sample size as shown in Figure 13-3 per bay.

Surveys of resident mussel populations in North America

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 Pacific North America, and was likely introduced with the oyster *Crassostrea gigas* in the early 1900s (Fofonoff et al. 2003).

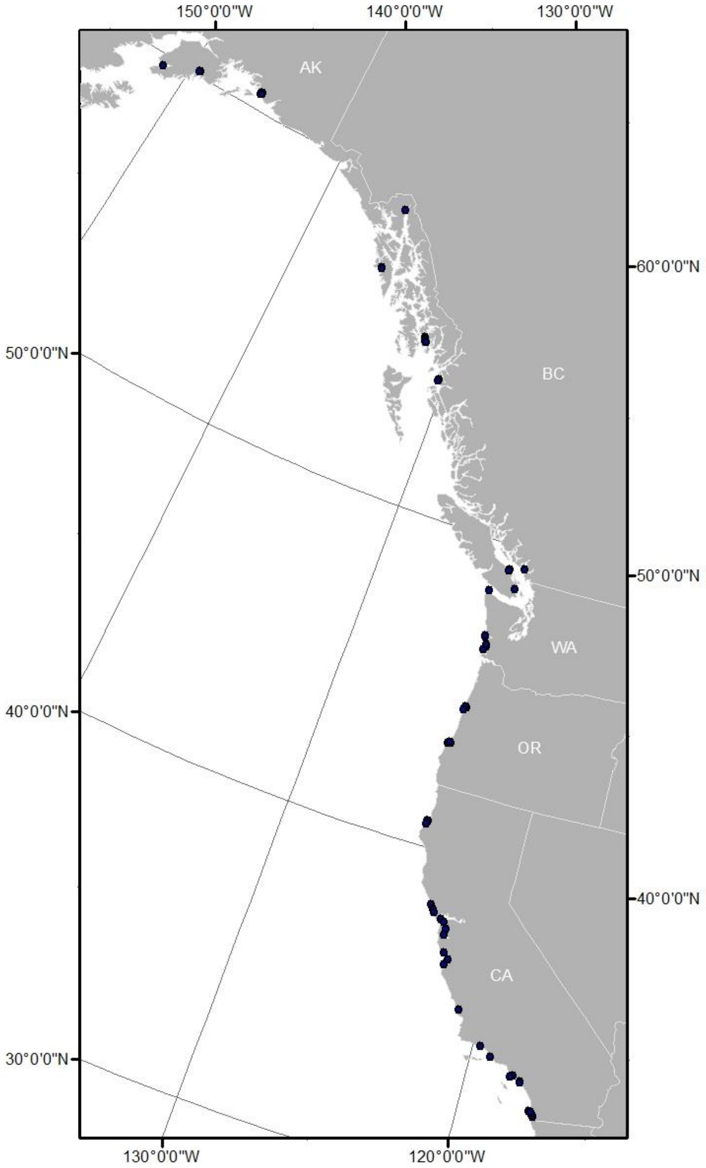

Figure 13-6. Mussel survey locations. Dark circles indicate location of sites sampled (n>50 mussels). No *Eutima* sp. were detected in any mussels screened from any location.

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 in Pacific North America, using field-based surveys and literature-based synthesis to detect new invasions. Second, we highlight 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 in Pacific 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 the assessment of whether JTMD was a plausible mechanism for any future introduction.

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 bar-code library developed during this project (see Chapter 8). Moreover, this 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 & Soule 1999; Ruiz et al. 2000; Solow & 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.

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 analysis is 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 (Figure 13-3 and Figure 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 Pacific 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 also be useful in identifying locations and taxa for future detection measures, to assess whether JTMD invasions have occurred.

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THEME V – Detection of Invasion

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 also established long term monitoring sites for detecting future introduction of JTMD macroalgal species. 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. We have selected several localities as recommended long term monitoring sites for detecting new invasions of JTMD macroalgae. Although our surveys continue, we have not, to date, found any new macroalgae populations in Pacific North America that are the result of invasions by the algae from JTMD.

Introduction

After being carried across the North Pacific on currents from Japan, marine debris items from the Great 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, the following research was conducted: 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 future introduction of JTMD macroalgal species.

The research objectives were 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

Surveying probable sites and habitats for new algal invasions

Field Surveys

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

Photo credit: Hideaki Maki

The sampling team traveled to sites in Alaska, British Columbia, Washington State, and Oregon in 2015 and 2016 (Table 14 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 were also sampled in May 2007). In Washington and Oregon, six floating docks, two jetties, and one bay were each surveyed 2-3 times to search for the new recruitment of JTMD species.

Visual searches were carried out for the larger JTMD algal species and collections of both large and small species were made 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.

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 State	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

Results

Surveys for algae in North America

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 found associated with JTMD (conspecifics) were identified during surveys of natural and artificial habitats (Table 14). All were 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.

British Columbia

The results of surveys in British Columbia are based on morphological and anatomical examination of the specimens collected (Table 14 and Appendix 14-1). Selected specimens were sequenced to confirm or expand these preliminary identifications. Of these species, only *Blidingia minima, Bryopsis sp., Cladophora sericea, Ulva intestinalis, Ulva lactuca, and Hincksia sandriana* were also reported on JTMD. *Ulva linza, Analipus japonicus, Petalonia fascia, Scytosiphon lomentaria, and Palmaria mollis*, 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 revealed the new occurrence of a JTMD species in 2015. A Japanese species of *Pyropia* that was heretofore unknown from British Columbia was discovered at Calvert Island, British Columbia (Lindstrom *in review*). 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 relocate the species at the same site it was collected at in 2015, no specimens were detected. Whether this means that the species no longer grows in BC, or it was just a bad year for the gametophytes of *Pyropia* (as we observed at our monitoring sites for other species of the genus and as the Heiltsuk First Nations found for the species they harvest each spring, *P. abbottiae*—Mike Reid, pers. comm.), remains to be seen. 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 and further analysis is required.

Alaska


Photo credit: Hideaki

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 also 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* (Ketchikan, Sitka), *Palmaria mollis* (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 14-1and Figure 14-2). We have made some surveys in natural habitat in Sitka and 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.

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

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

Discussion

Through the field surveys of selected natural populations from Alaska to Oregon, we have not found any introduced populations that can 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 in 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.

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Appendices

Appendix 14-1. Algae species observed in field surveys of North America

Appendix 14-1. Algae species observed in field surveys of North America

Those followed by an asterisk (*) are believed to be introduced species. Highlighted rows represent species also observed on JTMD.

Group	Field observed species	Tofino	Ucluelet	Bamfield	Ketchikan	Kodiak	Sitka	Prince Rupert
Browns	Costaria costata							1
Browns	Desmarestia ligulata	1						
Browns	Desmarestia viridis					1		
Browns	Ectocarpus commensalis				1		1	
Browns	Fucus distichus							1
Browns	Hincksia cf granulosa vs cf sandriana		1	1				
Browns	Hincksia sandriana				1		1	1
Browns	Leathesia marina			1				
Browns	Nereocystis luetkeana							1
Browns	Punctaria latifolia				1		1	
Browns	Saccharina “groenlandica”						1	1
Browns	Saccharina groenlandica	1						
Browns	Sargassum muticum*			1				
Browns	Scytosiphon lomentaria				1	1	1	
Greens	Acrosiphonia coalita							1
Greens	Blidingia minima	1				1		
Greens	Bryopsis plumosa							1
Greens	Bryopsis sp.			1				
Greens	Chaetomorpha sp.			1				
Greens	Cladophora cf sericea		1	1				
Greens	Cladophora sericea				1	1	1	1
Greens	Codium fragile subsp. californicum			1				
Greens	Derbesia marina					1		1
Greens	Percursaria percursa							1
Greens	Prasiola meridionalis							1
Greens	Rhizoclonium riparium				1	1	1	1
Greens	Saccharina latissima				1	1		
Greens	Ulva cf intestinalis	1	1					1
Greens	Ulva cf lactuca	1	1	1				
Greens	Ulva cf prolifera		1	1				1
Greens	Ulva linza							1
Greens	Ulva spp.				1	1	1	

Reds	Antithamnionella spirographidis*	1						
Reds	Ceramium cimbricum				1		1	
Reds	Ceramium gardneri							1
Reds	Ceramium kondoi*			1				
Reds	Ceramium pacificum			1				
Reds	cf Grateloupia californica			1				
Reds	Chondracanthus corymbiferus	1		1				
Reds	Erythrotrichia carnea				1	1	1	1
Reds	Hymenena sp.	1						
Reds	Mazzaella oregona	1						
Reds	Mazzaella splendens	1						
Reds	Membranoptera platyphylla	1						
Reds	Microcladia coulteri	1		1				
Reds	Palmaria mollis					1		
Reds	Polysiphonia brodiei*	1	1	1				
Reds	Polysiphonia hendryi	1						
Reds	Prionitis sternbergii			1				
Reds	Pyropia perforata	1						
Reds	Scagelia occidentale				1	1	1	1
	Total species	**15**	**6**	**16**	**11**	**11**	**11**	**18**
	JTMD species	**3**	**4**	**3**	**6**	**5**	**6**	**6**

THEME VI – Risk of Invasion

Chapter 15: The invasion risk of species associated with Japanese Tsunami Marine Debris in North America and Hawaii[8]

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Abstract

Marine debris from the Great Tsunami of 2011 is a novel transport vector for Japanese species to reach Pacific North America and Hawaii. Over 650 debris items attributed to the tsunami have been intercepted thus far and over 380 species of algae, invertebrates and fish have been identified associated with this Japanese tsunami marine debris (JTMD). Most of the species encountered are native to Japan, not currently present in North America or Hawaii, and their invasion risk is unknown. Thus, it is important to characterize the risk their introduction may pose to North American and Hawaiian ecosystems. Risk assessment is an important tool that can inform policy and management decisions about potential invasive species. Here we characterize the risk of individual invertebrate and algae species associated with JTMD using an established screening-level risk assessment tool – the Canadian Marine Invasive Screening Tool (CMIST). This tool scores both the probability and consequences (impacts) of an invasion for receiving ecosystems, to generate an overall risk score that encompasses assessor uncertainty. Higher-risk invertebrate and algae invaders were identified for different ecoregions on the Pacific coast of North American and Hawaii. 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 some of the assessed ecoregions while others like the sea star *Asterias amurensis*, the shore crab *Hemigrapsus sanguineus,* and the algae *Undaria*

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[8] A version of this chapter is in preparation for submission to a peer-reviewed journal.

pinnatifida have yet to invade large portions of the assessed ecoregions. However, most of the species assessed were considered relatively low to moderate risk, due to a lack of reported invasion history and impacts elsewhere. Based on CMIST scores for all taxa, the Northern California ecoregion had the highest median invasion risk while the Gulf of Alaska had the lowest, in part due to the reduced climate match with this ecoregion. The risk scores and lists provide key information that can be used to inform monitoring activities and raise awareness with stakeholders and the public.

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 meters and inundated 562 square kilometres 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 (Ministry of the Environment, Japan 2012), where many objects were colonized by Japanese coastal species.

While the rafting of organisms on marine debris is not a new phenomenon and has been occurring for centuries, especially on terrestrial and marine vegetation (Lewis et al. 2005; Thiel and Gutow 2005), human-mediated activities have drastically increased the amount of marine debris in our oceans (Barnes 2002; Gregory 2009), dominated by plastic which does not readily biodegrade like woody or plant material. Further, a number of recent studies have identified a wide variety of taxa that are able to colonize marine debris. For example, Barnes and Fraser (2003) found at least 10 species belonging to five phyla with the potential to invade the Southern Ocean and 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 therefore has the potential to deliver non-indigenous species (NIS) to novel locations, establish new invasions, and cause ecological and economic impacts. Given the unique nature of the Great Tsunami of 2011, combined with this rafting phenomenon, it is important to identify


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potential species associated with JTMD that could pose a risk to coastal ecosystems in North America (California to Alaska) and Hawaii.

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 and accurate 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 allow ranking of species based on potential risk thereby providing a prioritized list of NIS for potential management intervention or policy development.


Photo credit: Hideaki Maki

To inform potential monitoring, management or policy planning around Japanese species potentially arriving on JTMD, a method that allows prioritization is desired. A recently developed marine screening-level risk assessment tool, 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 impacts. Further, CMIST uses Monte Carlo simulation to allow uncertainty to be captured explicitly in the risk assessment score. Thus, we applied CMIST to species associated with JTMD to characterize the relative risk posed to Pacific North American and Hawaiian ecosystems.

Methods

Species associated with JTMD

Over 600 JTMD objects arriving on the shores of Hawaii and Pacific North America have been opportunistically sampled for invertebrate, algae, and fish species since June 2012 (when JTMD began arriving en masse). Interception and sampling of JTMD items has continued through the date of writing (March 2017) with more than 380 taxa representing various invertebrates, algae, and fish species identified in association with JTMD items thus far (J. Carlton, unpublished data.). However, our assessment of JTMD species risk has been limited to those invertebrate and algae species identified as of May 2016, though with species removed and names updated as necessary through May 2017. Biological samples were processed morphologically with genetic verification for some organisms and identified to the lowest taxonomical level possible. All invertebrates and algae identified to the species level were retained for screening for potential invasion risk (N=193). Higher level taxonomic identifications 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 (see also Chapter 12). This information came from a variety of sources (e.g. primary publications, reports, databases, internet searches, etc.) in both the international and Japanese literature. The resulting database was then used in the risk assessment.

CMIST risk assessment

The potential risk of JTMD species arriving to Hawaii and Pacific North America was determined using the Canadian Marine Invasive Species Tool (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 question is scored on a scale between 1 and 3 (‘Low’ = 1 to ‘High’ = 3) (Drolet et al. 2016; Appendix 15.1). 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 a 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 certainy’ = 3) for each question. 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). 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 species known to have been associated with JTMD were calculated by two assessors independently using CMIST, with a 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 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 Pacific North America that were known to have received JTMD (Figure 15-1; Gulf of Alaska, North American Pacific Fijordland, Oregon, Washington, Vancouver Coast and Shelf, Northern California, and Hawaii). 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 (Maximenko et al. 2012; Lebreton and Borreo 2013). 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 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. 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, respectively, of the combined algae and invertebrate species per region were reported. The effects of region and inter-assessor variability were assessed using Repeated Measures General Linear Model for all taxa.

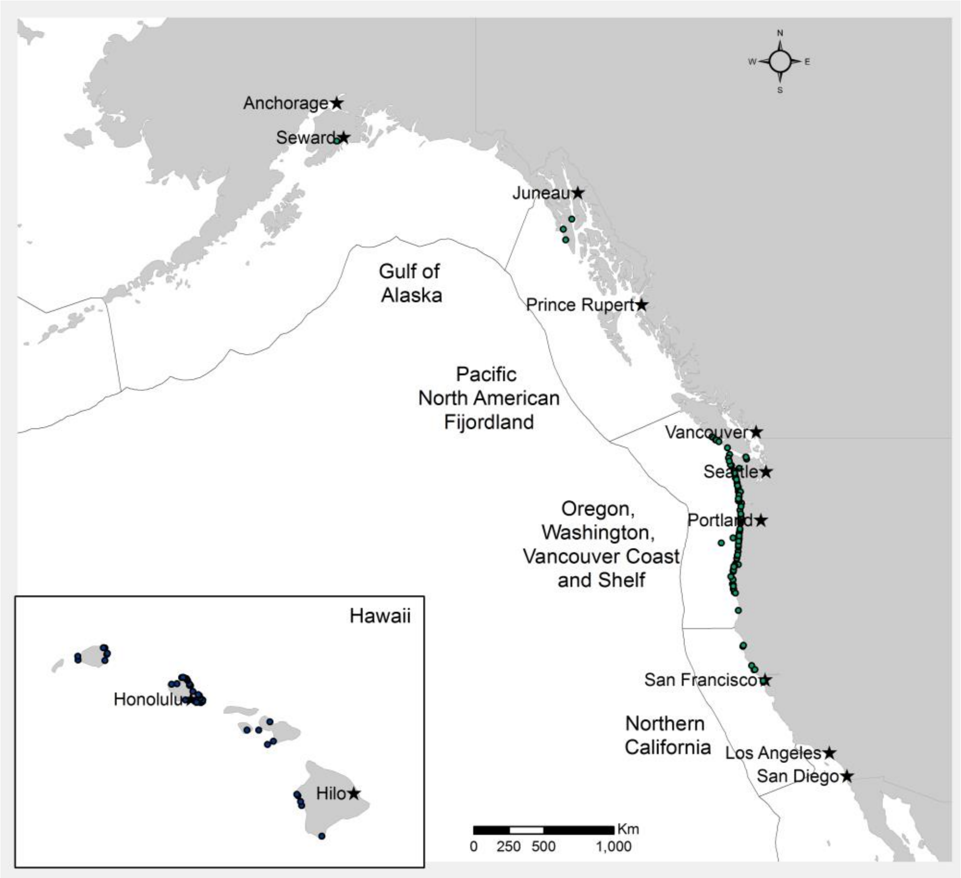

Figure 15-1. Ecoregions of Pacific North America and Hawaii, and JTMD landings (blue dots).

Results

Monte Carlo adjusted risk scores were obtained for 193 species in each of the five ecoregions (Appendix 15-2). There was no significant difference between assessors ($F = 0.680$, $p = 0.413$, $df = 1$) and therefore Monte Carlo adjusted risk scores were averaged across assessors. Risk varied across species and ecoregions. The higher risk species (relative to other species scored from JTMD) across all ecoregions were well-known global invaders including: the mussel *Mytilus galloprovincialis*, the ascidian *Didemnum vexillum,* the sea star *Asterias amurensis*, and the algae *Undaria pinnatifida* (Figure 15-2).

Overall, Northern California had the highest median and individual maximum risk scores (Table 15-1) and adjusted risk scores were significantly different by region (Figure 15-3; repeated measures GLM: $F = 15.646$, $p < 0.001$, $df = 4$). In contrast, Hawaii had the highest cumulative risk (species risk summed across all species), and Oregon, Washington, Vancouver coast and shelf had the lowest cumulative risk. Hawaii had the highest number of species associated with JTMD that are not native to the region (187), and therefore the highest number of potential invasions rather than higher risk species on average. The ecoregions had differing levels of invasion history and some of the JTMD species had already been introduced by other vectors (Figure 15-3). In fact, of the higher risk invertebrate and algae species assessed using CMIST, the number of existing invaders in the five assessed ecoregions ranged from 15 in Northern California to 8 in Hawaii (see asterisks in Figure 15-3).

Table 15-1. Summary statistics of the entire suite of non-native species (NIS, cryptogenic and unknown species status) scored. Native species scores were excluded for each ecoregion. Cumulative risk refers to the sum of all risk scores for the ecoregion, n is the number of species included for each ecoregion.

Region	Median	Lower 95% CI	Upper 95% CI	Cumulative Risk	Min score	Max score	n
Gulf of Alaska	2.60	2.53	2.70	492.41	1.69	5.78	177
North American Pacific Fijordland	2.66	2.55	2.72	511.77	1.70	6.03	181
Oregon, Washington, Vancouver coast & shelf	2.69	2.61	2.78	484.85	1.69	6.62	164
Northern California	2.72	2.63	2.77	524.51	1.83	6.86	175
Hawaii	2.67	2.61	2.73	532.49	1.76	5.94	187

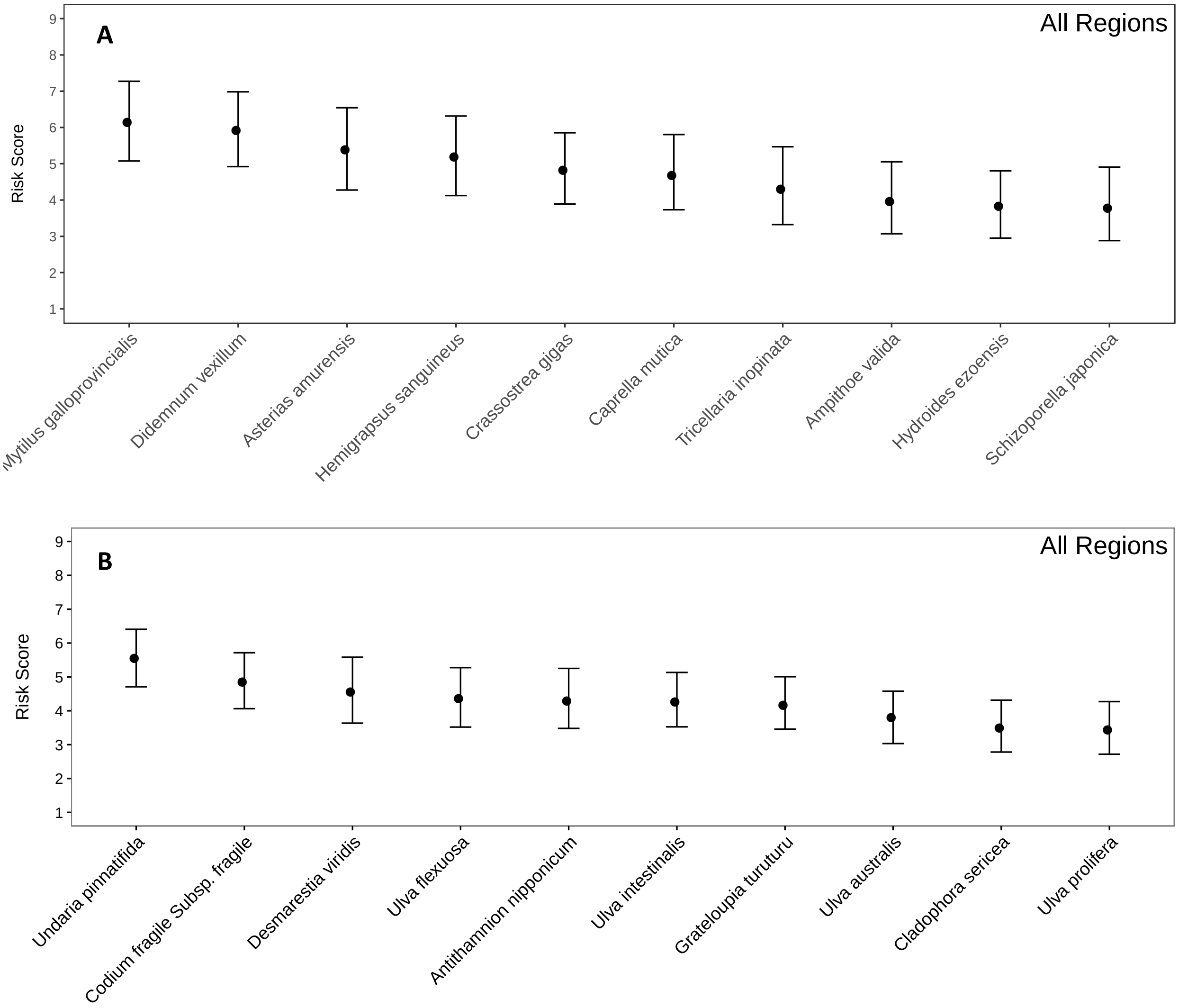

Figure 15-2. Ten highest risk species of invertebrates (A) and algae (B), averaged over all ecoregions from which the species were not native. Error bars are 95% confidence intervals calculated using Monte Carlo simulation.

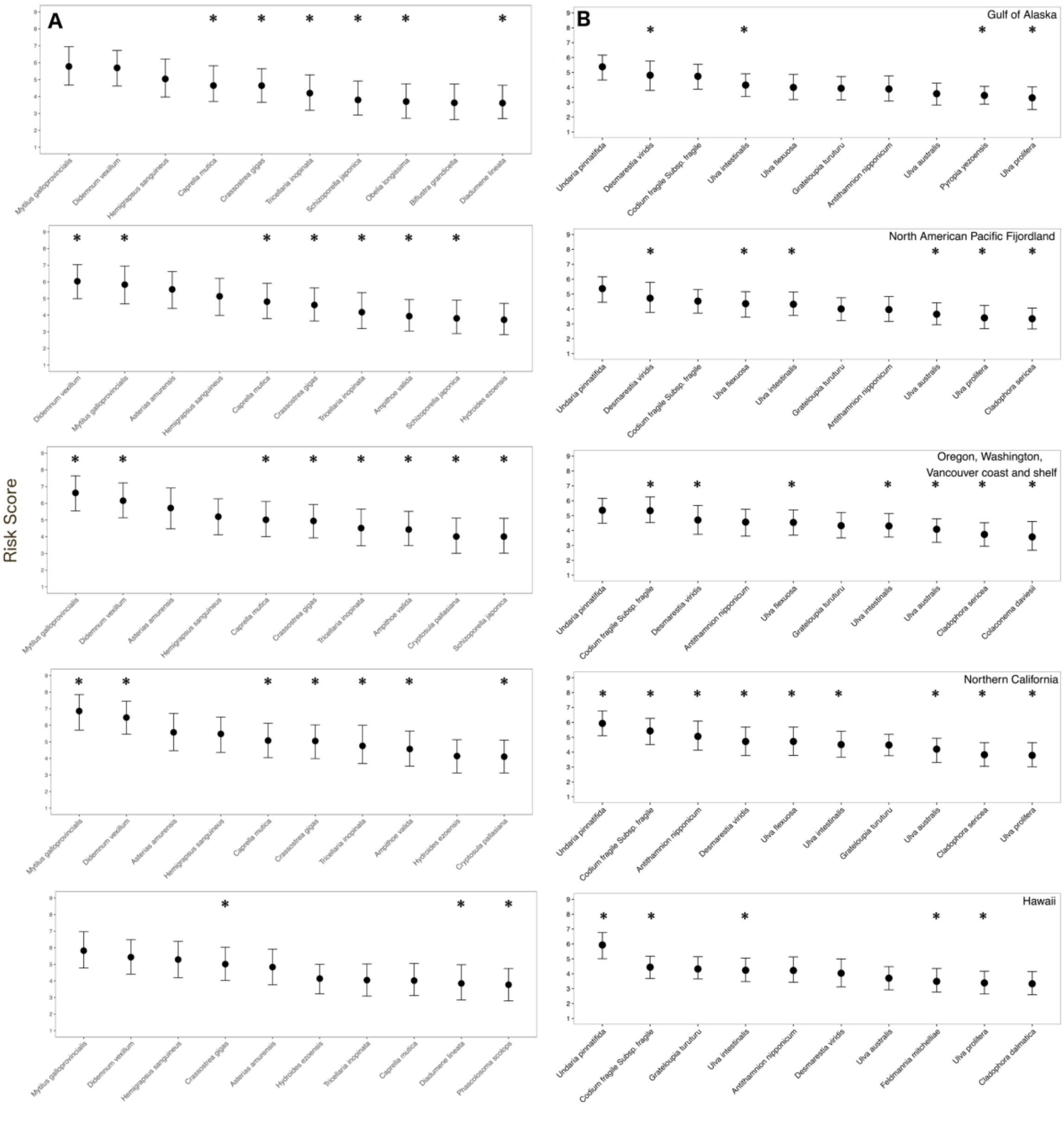

Figure 15-3. Ten highest risk species of invertebrates (A) and algae (B) by ecoregion: Gulf of Alaska, North American Pacific Fijordland, Oregon, Washington, Vancouver Coast and Shelf, Northern California, and Hawaii. Error bars are 95% confidence intervals calculated using Monte Carlo simulation. Asterisks denote species already present in the ecoregion.

Discussion

A large diversity of non-indigenous species reached North American coasts via rafting on JTMD, including species with well-documented global invasion histories and documented impacts (e.g., *Mytilus galloprovincialis*, *Didemnum vexillum*, *Asterias amurensis, Hemigrapsus sanguineus,* and *Undaria pinnatifida*). Many of these species also have been transferred to other global regions by a variety of invasion vectors including commercial and recreational vessels and via aquaculture-mediated movements. Although have already established in our focal ecoregions, newly arriving individuals on JTMD may pose additional risks. 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; Kolbe et al. 2007; Facon et al. 2008; Geller et al. 2010).

Due to a scarcity of information, there were many NIS on JTMD that received low scores in CMIST. Species that are not well studied do not have sufficient information available to warrant higher scores on screening questions about environmental requirements, possible vectors, and possible impacts, which results in a lower score, albeit with higher uncertainty. Thus, these species scored lower generally either because they scored lower for invasion probability and/or there were no documented impacts. The invasion probability questions in CMIST are related to the potential for species to arrive, survive, reproduce, and potentially spread, based on the known history of the species. With the exceptions of Hawaii and Gulf of Alaska, most of the species assessed here had relatively good climate match between the source location in Japan and the receiving environments along the west coast of North America (i.e., North American Pacific Fjordland to Northern California). Of the five ecoregions assessed here, Northern California arguably has the highest climate/habitat match to the Honshu region of Japan where most JTMD species are believed to have originated. However, since most of these species are not known from other invasion vectors they would


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have scored lower in CMIST for arrival and spread questions despite potentially scoring higher for survival and reproduction potential. Each question is weighted equally in the overall score, which means these survival and reproduction qualities 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. Assessing the potential impacts of species with no prior invasion history remains a challenge despite efforts to predict impacts (e.g., Blackburn et al. 2014; see Chapter 12). 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). Thus, the highest risk species identified here were well-known invaders with previously documented, significant impacts in other parts of the world, like *Mytilus galloprovincialis* and *Didemnum 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 exists many examples where a species introduction has unexpected and disproportionate impacts based on its earlier invasion history or lack thereof (Carlton and Geller 1993). Unfortunately only time will tell if such a species reaches Pacific North America or Hawaii on JTMD.

Risk varied by region, with Northern California having the highest median risk scores among ecoregions and the Gulf of Alaska having the lowest. Cumulative risk from all JTMD associated species was highest for Hawaii, as it would be potentially exposed to the largest number of novel species. Ecoregions like Northern California and Hawaii have well documented invasion histories (Cohen and Carlton 1998; Cox 1999). In Northern California, 15 of the 20 highest risk species have already been introduced by other vectors. In contrast, the Gulf of Alaska is relatively less invaded, with 10 of the 20 highest risk species already present. The differing risk reflects the different invasion vectors, habitat types, and climate matches to donor ecoregions and invasion hotspots like San Francisco Bay (Ruiz et al. 2011b).

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Cathryn Clarke Murray

In addition to the documented free-living 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 North American ecosystems. The high risk species *Mytilus* *galloprovincialis* and its hydroid parasite, *Eutima*, were both detected on JTMD objects (Calder et al 2014; Chapter 7). While the risk of known parasites and associated species are addressed in one question of CMIST, the data on parasite diversity for many invertebrate group remains limited and, where present, there is often considerable uncertainty about the potential consequences of parasites and diseases. Also, a number of parasites have more complex life history strategies requiring multiple hosts to complete their life cycle. It is possible that newly arriving JTMD species could also 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.

Another unexpected consequence occurred with the historical transport of the Pacific oyster (*Crassostrea gigas*) and the Atlantic oyster (*Crassostrea virginica*) where entire oyster communities were imported to North American Pacific coastal ecosystems for aquaculture production 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 of North America. For example, several NIS were introduced with oysters to California (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*.

As with all screening-level risk assessments, readily available information is critical. Perhaps not surprisingly, for this assessment there was considerable variation in available literature among JTMD species assessed. Two advantages of the CMIST tool as applied here include the explicit incorporation of uncertainty in the risk score and the tool relies on fewer questions to be answered compared to other risk assessment tools (Drolet et al. 2016). 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. Similarly, taxonomic resolution was required to apply CMIST so only those species with fully ascribed binomials were run through the tool. Thus, organisms only resolved to higher taxonomic levels were not screened, including some that could be higher risk. For example, the shipworm *Psiloteredo* on JTMD was a new species that has not previously been recorded in Pacific North America and

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may pose a risk similar to other species of shipworm such as the global invader *Teredo navalis* (Hoppe 2002; Paalvast and van der Velde 2011).

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 experimentally-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 (Mooney and Drake 1986; Ehrlich 1989; Sakai et al. 2001). In addition to the role 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 high risk in arctic areas even though the probability of survival might be very low.

The application of CMIST to JTMD species confirmed the presence of high risk NIS on JTMD objects: three JTMD species (*Asterias amurensis*, *Mytilus galloprovincialis*, and *Undaria pinnatifida*) 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 reduce the risk of invasion by reducing the propagule load to native ecosystems, which can lower establishment success of many NIS (sensu Lockwood et al. 2005; Simberloff 2009). Given the time lag in invasion population dynamics (Crooks et al. 1999) and detection thresholds (Regan et al. 2006; Fagan et al. 2002; Neubert and Parker 2004; Rout et al. 2009), continued monitoring in the coming decades is warranted, especially for those higher risk species identified here.

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Appendices

Appendix 15.1. Full list of CMIST questions and scoring rubric

Appendix 15.2. Full list of JTMD species, ecoregions and risk scores

Appendix 15.1: Full list of CMIST questions and scoring rubric

Question		Scoring rubric and description of answers
1	Is the species established in the assessment area?	[1] No [2] Observed but not reported as established [3] Yes
2	How frequently and in what numbers is the species expected to arrive into the assessment area?	[1] Infrequently in low numbers [2] Frequently in low numbers or infrequently in high numbers [3] Frequently in high numbers
3	How much of the assessment area offers suitable habitat for the species?	[1] Negligible proportion of the assessment area [2] Moderate proportion of the assessment area [3] Most of the assessment area
4	How much of the assessment area offers suitable environmental conditions for the species to survive?	[1] Negligible proportion of the assessment area [2] Moderate proportion of the assessment area [3] Most of the assessment area
5	Are the species' reproductive requirements available in the assessment area?	[1] Almost never [2] Sometimes [3] Almost always
6	To what extent could natural control agents slow the species' population growth in the assessment area?	[1] Likely to severely restrict population growth [2] Could slow population growth [3] Unlikely to slow population growth
7	What is the range of the species' potential natural dispersal in the assessment area?	[1] Very limited range [2] Moderate range [3] Wide range
8	What is the range of the species' potential dispersal in the assessment area from anthropogenic mechanisms?	[1] Very limited range [2] Moderate range [3] Wide range
9	What level of impact could the species have on population growth of other species in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
10	What level of impact could the species have on communities in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
11	What level of impact could the species have on habitat in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas

12	What level of impact could the species have on ecosystem function in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
13	What level of impact could the species' associated diseases, parasites, or travellers have on other species in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
14	What level of genetic impact could the species have on other species in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
15	What level of impact could the species have on at-risk or depleted species in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
16	What level of impact could the species have on aquaculture and commercially fished species in the assessment area?	[1] Low or no impact [2] High impact in few areas or moderate impact in many areas [3] High impact in many areas
17	Is the species known or generally considered to be invasive anywhere in the world?	[1] No [2] No, but has traits related to invasiveness [3] Yes

Appendix 15-2. Full list of JTMD species, ecoregions and risk scores

Species	Gulf of Alaska	Northern Fijordland	Oregon, Washington, Vancouver Coast and Shelf	Northern California	Hawaii	Overall
Invertebrates						
Phylum Annelida						
Amblyosyllis speciosa	2.520	2.522	2.658	2.509	2.390	2.520
Arabella sp. *semimaculata* group[i]	2.639	2.770	Native	3.105	2.735	2.812
Eulalia quadrioculata	2.762	2.808	Native	Native	2.629	2.733
Eulalia viridis-complex	2.493	2.508	Native	2.589	2.503	2.523
Halosydna brevisetosa-complex	2.872	3.044	Native	Native	2.560	2.825
Harmothoe imbricata	3.098	3.102	3.083	3.091	2.673	3.009
Hydroides ezoensis	3.534	3.721	3.786	4.141	4.139	3.864
Nereis pelagica	Native	Native	Native	Native	3.095	3.095
Perinereis nigropunctata	2.514	2.540	2.570	2.643	Native	2.567
Pygospio californica	2.719	2.805	Native	3.064	2.721	2.828
Spirobranchus polytrema	3.107	3.174	3.314	3.482	3.443	3.304
Syllis elongata-complex	2.569	2.722	Native	Native	2.732	2.675
Syllis gracilis-complex	2.463	2.455	Native	2.502	2.727	2.537
Syllis hyalina-complex	2.487	2.657	2.668	2.662	2.666	2.628
Trypanosyllis zebra	2.318	2.339	2.385	2.490	Native	2.383
Phylum Bryozoa						
Aetea anguina	3.067	3.112	3.232	3.308	3.149	3.174
Arbocuspis n. sp.[ii]	2.486	2.501	2.483	2.599	2.681	2.550
Biflustra grandicella	3.629	3.624	3.691	3.839	3.733	3.703
Biflustra irregulata	2.784	2.866	2.846	2.869	2.864	2.846
Callopora craticula	Native	Native	2.355	2.210	2.161	2.242
Cauloramphus spinifer[iii]	2.669	2.605	2.608	2.614	2.420	2.583
Celleporella hyalina	Native	Native	Native	Native	3.097	3.097
Celleporina porosissima	2.878	2.877	2.879	2.891	2.609	2.827
Cryptosula pallasiana	3.517	3.600	4.010	4.106	3.357	3.718
Escharella hozawai	2.712	2.705	2.700	2.703	2.520	2.668
Exochella tricuspis	2.692	2.708	2.774	2.767	2.714	2.731
Membranipora villosa[iv]	Native	2.760	Native	Native	2.511	2.635
Microporella borealis	2.840	2.835	2.839	2.847	2.649	2.802
Schizoporella japonica	3.800	3.809	4.006	4.099	3.361	3.815
Smittoidea spinigera	2.722	2.740	2.746	2.736	2.729	2.735
Tricellaria inopinata	4.199	4.177	4.515	4.757	4.045	4.339
Tubulipora misakiensis	2.766	2.770	2.760	2.770	2.513	2.716
Tubulipora pulchra	2.755	2.826	2.796	2.804	2.757	2.788

Phylum Cercozoa						
Gromia "oviformis"	2.673	2.688	2.663	2.799	2.664	2.697
Phylum Chelicerata						
Endeis nodosa	2.316	2.404	2.427	2.708	2.882	2.547
Halacarellus schefferi	2.634	2.443	2.377	2.347	2.367	2.434
Phylum Chordata						
Didemnum vexillum	5.697	6.034	6.154	6.467	5.433	5.957
Phylum Cnidaria						
Amphisbetia furcata	2.501	2.552	Native	Native	2.481	2.512
Bougainvillia muscus	2.951	3.130	3.485	3.625	3.665	3.371
Diadumene lineata	3.613	3.648	3.849	3.969	3.848	3.785
Eutima japonica	2.922	2.967	3.223	3.214	3.325	3.130
Halecium tenellum	Native	Native	Native	Native	2.414	2.414
Hydrodendron gracilis	Native	Native	Native	Native	2.568	2.568
Metridium dianthus	Native	Native	Native	Native	3.136	3.136
Obelia longissima	3.704	3.706	3.779	3.861	3.255	3.661
Orthopyxis caliculata	3.070	3.018	Native	2.909	2.632	2.907
Orthopyxis platycarpa[v]	2.579	2.493	2.568	2.399	2.428	2.493
Plumularia setacea	2.898	2.976	Native	3.077	2.790	2.935
Pocillopora damicornis	1.993	1.995	1.998	2.150	Native	2.034
Sertularella mutsuensis	2.231	2.243	2.297	2.238	2.145	2.231
Phylum Crustacea						
Ampithoe lacertosa	3.085	3.291	3.430	3.524	2.744	3.215
Ampithoe valida	3.511	3.940	4.430	4.566	3.566	4.003
Balanus crenatus	Native	Native	Native	Native	2.502	2.502
Balanus glandula	Native	Native	Native	Native	3.639	3.639
Balanus trigonus	2.704	2.758	2.888	Native	Native	2.783
Caprella cristibrachium	2.376	2.426	2.430	2.523	2.423	2.436
Caprella mutica	4.650	4.812	5.013	5.077	4.018	4.714
Caprella penantis	3.239	3.342	3.633	3.804	3.757	3.555
Chthamalus challengeri	3.185	3.269	3.724	3.947	3.637	3.552
Dactylopodamphiascopsis latifolius	2.450	2.533	2.518	2.596	2.458	2.511
Dynoides spinipodus	2.494	2.523	2.571	2.657	2.561	2.561
Gammaropsis japonica	2.063	2.068	2.343	2.345	2.179	2.200
Harpacticus compsonyx[vi]	2.445	2.521	2.568	2.555	2.469	2.512
Harpacticus nicaeensis	2.407	2.401	2.460	2.490	2.555	2.463
Harpacticus septentrionalis	Native	2.672	2.766	2.715	2.477	2.658
Harpacticus sp. -flexus group[vii]	2.564	2.571	2.566	2.558	2.407	2.533
Hemigrapsus sanguineus	5.041	5.134	5.199	5.478	5.289	5.228
Heterolaophonte discophora	Native	2.718	2.728	2.739	2.461	2.662
Ianiropsis serricaudis	3.235	3.234	3.624	3.801	3.121	3.403
Jassa marmorata-complex	3.439	3.630	3.821	3.922	3.222	3.607

Megabalanus rosa	2.876	2.858	3.127	3.232	3.450	3.109
Megabalanus zebra	2.646	2.755	2.832	3.068	3.287	2.918
Oedignathus inermis	Native	Native	Native	Native	2.170	2.170
Paralaophonte congenera	2.500	2.548	Native	2.486	2.393	2.482
Paramphiascella fulvofasciata	2.298	2.306	2.393	2.374	2.181	2.310
Parastenhelia spinosa	Native	2.541	2.597	2.552	2.298	2.497
Parathalestris intermedia	2.778	2.780	2.613	2.551	2.484	2.641
Pseudoctomeris sulcata	2.528	2.515	2.522	2.594	2.758	2.583
Sarsamphiascus minutus	2.700	2.691	2.722	2.787	2.523	2.685
Sarsamphiascus varians group	2.351	2.375	2.372	2.365	2.794	2.451
Semibalanus cariosus	Native	Native	Native	Native	2.192	2.192
Sphaerozius nitidus	2.665	2.764	2.899	3.005	3.120	2.891
Stenothoe crenulata-complex	2.736	2.820	2.888	3.067	3.216	2.945
Xestoleberis setouchiensis	2.566	2.554	2.537	2.560	2.631	2.570
Zeuxo normani	Native	Native	Native	Native	2.613	2.613
Phylum Echinodermata						
Aphelasterias japonica	2.745	2.832	2.819	2.843	2.808	2.809
Asterias amurensis	Native	5.549	5.718	5.573	4.834	5.418
Havelockia versicolor	2.392	2.371	2.381	2.369	2.905	2.484
Patiria pectinifera	2.484	2.476	2.526	2.604	2.654	2.549
Temnotrema sculptum	2.425	2.418	2.428	2.550	2.676	2.500
Phylum Foraminifera						
Cibicides lobatulus[viii]	2.807	2.672	Native	2.803	2.866	2.787
Phylum Hexapoda						
Telmatogeton japonicus	2.769	2.841	2.895	3.136	3.038	2.936
Phylum Mollusca						
Arca navicularis	2.299	2.304	2.288	2.296	2.661	2.369
Bankia bipennata	2.624	2.622	2.672	2.710	2.829	2.692
Bankia carinata	2.715	2.711	2.709	2.729	2.838	2.740
Barbatia virescens	2.300	2.316	2.410	2.516	2.751	2.459
Crassostrea gigas	4.653	4.615	4.931	5.049	5.028	4.855
Crepidula onyx	3.143	3.145	3.552	3.565	3.634	3.408
Dendostrea folium	2.738	2.753	2.884	2.892	3.296	2.912
Dendronotus frondosus	2.720	2.709	Native	2.474	2.222	2.531
Dolabella auricularia	2.537	2.517	2.605	2.616	Native	2.569
Hermissenda crassicornis	2.842	2.946	Native	3.020	2.441	2.812
Hiatella orientalis[x]	3.010	3.048	3.204	3.231	2.821	3.063
Hyotissa chemnitzi	2.410	2.449	2.528	2.562	2.590	2.508
Hyotissa numisma	2.478	2.486	2.492	2.569	2.954	2.596
Isognomon legumen	2.331	2.328	2.336	2.333	2.887	2.443
Laevichlamys irregularis	2.529	2.538	2.606	2.677	2.841	2.638
Limaria hakodatensis	2.690	2.681	2.706	2.759	2.673	2.702
Lithophaga curta	2.328	2.386	2.416	2.474	2.572	2.435

Lyrodus takanoshimensis	2.837	2.817	3.036	2.951	2.931	2.914
Mitrella moleculina	2.497	2.515	2.491	2.512	2.727	2.548
Mizuhopecten yessoensis[xi]	2.892	2.919	2.916	2.858	2.517	2.821
Modiolarca cuprea[xii]	2.461	2.448	2.464	2.587	2.669	2.526
Modiolus nipponicus	2.416	2.433	2.424	2.415	2.602	2.458
Mopalia seta	2.770	2.773	2.783	2.759	2.440	2.705
Mytilisepta virgata[xiii]	2.449	2.443	2.460	2.448	2.609	2.482
Mytilus coruscus[xiv]	2.589	2.677	2.844	2.958	2.668	2.747
Mytilus galloprovincialis	5.780	5.833	6.622	6.857	5.823	6.183
Mytilus trossulus	Native	Native	Native	Native	3.487	3.487
Nipponacmea habei	2.599	2.578	2.667	2.656	2.501	2.600
Pascahinnites coruscans	2.560	2.560	2.551	2.564	3.034	2.654
Pinctada imbricata	2.275	2.283	2.352	2.378	2.828	2.423
Reishia bronni[xv]	2.566	2.550	2.645	2.760	2.705	2.645
Scaeochlamys squamata	2.584	2.589	2.693	2.761	2.826	2.691
Sphenia coreanica	2.791	2.775	3.045	3.353	3.522	3.097
Spondylus cruentus[xvi]	2.447	2.465	2.446	2.457	2.615	2.486
Teredo navalis	3.455	3.508	3.704	3.919	3.550	3.627
Teredothyra smithi	2.297	2.305	2.301	2.295	2.667	2.373
Phylum Nemertea						
Oerstedia dorsalis	2.866	Native	2.963	2.915	2.540	2.821
Quasitetrastemma nigrifrons[xvii]	2.484	2.478	Native	2.634	2.416	2.503
Phylum Sipuncula						
Phascolosoma scolops	2.945	3.013	3.108	3.350	3.769	3.237
Algae						
Phylum Chlorophyta						
Blidingia minima	2.133	2.261	2.245	2.244	1.928	2.162
Blidingia subsalsa	2.353	2.308	2.306	2.304	2.205	2.295
Bryopsis hypnoides	2.226	2.232	2.506	2.569	2.378	2.382
Bryopsis plumosa	2.139	2.139	2.372	2.451	2.323	2.285
Chaetomorpha aerea	1.839	2.019	2.223	2.274	2.526	2.176
Cladophora albida	2.621	2.798	2.856	2.866	2.537	2.736
Cladophora dalmatica	3.147	3.143	3.345	3.344	3.329	3.261
Cladophora sericea	3.249	3.342	3.738	3.826	Native	3.539
Codium fragile subsp. Fragile	4.742	4.526	5.334	5.425	4.441	4.894
Halochlorococcum moorei	2.175	2.196	2.193	1.828	1.904	2.059
Ulothrix implexa	2.173	2.114	2.116	1.963	1.824	2.038
Ulva australis	3.570	3.646	4.085	4.201	3.702	3.841
Ulva compressa	2.679	2.660	2.667	2.742	2.929	2.735
Ulva flexuosa	3.994	4.353	4.544	4.716	Native	4.402
Ulva intestinalis	4.151	4.312	4.305	4.508	4.234	4.302
Ulva lactuca	2.565	2.625	2.635	2.689	2.624	2.628
Ulva linza	3.143	3.154	3.214	3.204	3.253	3.194
Ulva prolifera	3.295	3.400	3.511	3.783	3.385	3.475
Ulva simplex	1.796	1.799	1.998	2.061	2.052	1.941

Phylum Cyanobacteria						
Scytonematopsis crustacea	2.733	2.752	2.730	2.749	2.872	2.767
Phylum Phaeophyta						
Alaria crassifolia	2.311	2.284	2.271	2.281	1.941	2.218
Analipus japonicus	2.531	2.475	2.474	2.407	2.102	2.398
Desmarestia japonica	2.505	2.523	2.696	2.699	2.467	2.578
Desmarestia viridis	4.812	4.723	4.708	4.716	4.036	4.599
Ectocarpus penicillatus	2.320	2.318	2.329	2.295	2.166	2.286
Feldmannia irregularis	2.099	2.198	2.366	2.380	2.564	2.322
Feldmannia mitchelliae	2.604	2.683	2.944	3.364	3.486	3.016
Hincksia granulosa	2.193	2.200	2.382	2.510	2.318	2.321
Hincksia sandriana	2.191	2.239	2.353	2.541	2.290	2.323
Kuckuckia spinosa	2.204	2.209	2.347	2.332	2.568	2.332
Mutimo cylindricus	2.558	2.711	2.930	3.194	2.725	2.823
Petalonia fascia	2.279	2.385	2.451	2.569	2.435	2.424
Petalonia zosterifolia	2.355	2.291	2.284	2.299	2.068	2.259
Protectocarpus speciosus	2.362	2.365	2.444	2.708	2.554	2.487
Pseudolithoderma subextensum	2.281	2.181	2.114	2.128	2.193	2.179
Scytosiphon gracilis	2.373	2.543	2.753	2.725	2.353	2.550
Scytosiphon lomentaria	2.394	2.618	2.608	2.581	2.276	2.495
Sphacelaria rigidula	2.309	2.318	2.444	2.452	2.332	2.371
Sphacelaria solitaria	2.248	2.250	2.386	2.388	2.335	2.321
Stephanocystis osmundacea	1.946	1.942	2.172	Native	1.992	2.013
Undaria pinnatifida	5.379	5.366	5.360	5.932	5.935	5.595
Phylum Rhodophyta						
Acrochaetium microscopicum	2.632	2.597	2.682	2.683	3.184	2.756
Antithamnion nipponicum	3.888	3.955	4.569	5.058	4.220	4.338
Ceramium cimbricum	2.547	2.349	2.839	2.794	2.807	2.667
Chondrus giganteus	2.857	2.670	2.926	2.630	2.533	2.723
Chondrus yendoi	2.032	2.174	2.413	2.399	2.427	2.289
Colaconema daviesii	3.139	3.191	3.570	3.573	2.692	3.233
Colaconema pacificum	2.309	2.251	Native	2.319	1.889	2.192
Erythrotrichia incrassata	2.430	2.448	2.454	2.437	2.303	2.414
Grateloupia livida	2.347	2.351	2.626	2.720	2.660	2.541
Grateloupia turuturu	3.933	4.000	4.327	4.479	4.321	4.212
Leptofauchea rhodymenioides	2.053	2.044	2.135	2.137	2.313	2.137
Meiodiscus spetsbergensis	2.296	2.343	2.339	2.076	1.963	2.203
Neodilsea yendoana	2.333	2.206	2.059	2.007	1.936	2.108
Neosiphonia japonica	2.512	2.784	2.901	2.94	2.974	2.822
Palmaria mollis	2.383	2.365	Native	2.381	1.831	2.240
Polysiphonia morrowii	3.008	3.269	3.321	3.333	3.083	3.203

Polysiphonia scopulorum var. villum	2.992	3.089	3.317	3.307	2.924	3.126
Porphyrostromium japonicum	1.691	1.702	1.692	1.951	1.989	1.805
Ptilota filicina	2.102	2.077	Native	Native	1.756	1.978
Pyropia yezoensis	3.455	3.154	3.270	3.165	2.727	3.154

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*

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 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 in the North Pacific: ballast water, hull fouling, aquaculture and ornamental trade. Eight variables relating to different stages of the invasion process: source, transit, delivery, and impact were used to compare vectors. Variables included entrainment with the vector, species richness per shipment, number of shipments, abundance per shipment, survivorship potential, shipment duration, release to environment, and environment match. JTMD scored high only for three of the risk variables: entrainment with the vector, number of shipments, and 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 but is of lower risk because of the decaying nature of JTMD compared to ongoing shipping activities. To date, our surveys have not detected any species establishment attributable to JTMD, but there is a number of higher-risk species associated with JTMD, many of which have previously been introduced to at least one ecoregion in Pacific North America. There is overlap with the species found on JTMD and those associated with these other vectors but most importantly, these other vectors continue to operate in Pacific North America and many are increasing in intensity.

Introduction

The Great Tsunami of 2011 washed an estimated 5 million tons of debris into the Pacific Ocean. This debris differs from historic and natural marine debris in that the anthropogenic materials are largely non-biodegradable materials including plastic, fiberglass, styrofoam, and preserved wood, which allows these materials to reach distant shores without degrading appreciably.

When tsunami debris began arriving in North America and Hawaii, it was discovered that living coastal Japanese species were attached or entrained (see Chapters 7-10), highlighting the potential 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 & Oceans Canada 2003; International Council for the Exploration of the Sea (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 the ballast water and sediments (Flagella *et al.* 2007; Hayes and Hewitt 2000; Lavoie 1999; Levings et al. 2004; MacIsaac et al. 2002), with hull fouling (Coutts and Taylor 2004; Drake and Lodge 2007; Godwin 2003; Gollasch 2002; Lewis et al. 2004; Sylvester et al. 2011) and sea chests (Coutts et al. 2007; Coutts and Taylor 2004; Frey et al. 2009; Godwin 2003). 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; Zabin et al. 2014; Ashton et al. 2014). Additionally, the import of species for ornamental, seafood, bait and research activities have contributed to the introduction of species to North America (California Ocean Science Trust (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. There are 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. The vector risk assessment 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 Tsunami of 2011. Further, this process will create a general vector risk assessment model that can be applied at various scales to inform potential management of marine and terrestrial vectors of NIS.

Here we review the evidence acquired about the JTMD vector during the PICES ADRIFT (Assessing the Debris-Related Impact of Tsunami) project and compare the risk of species introduction to 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?

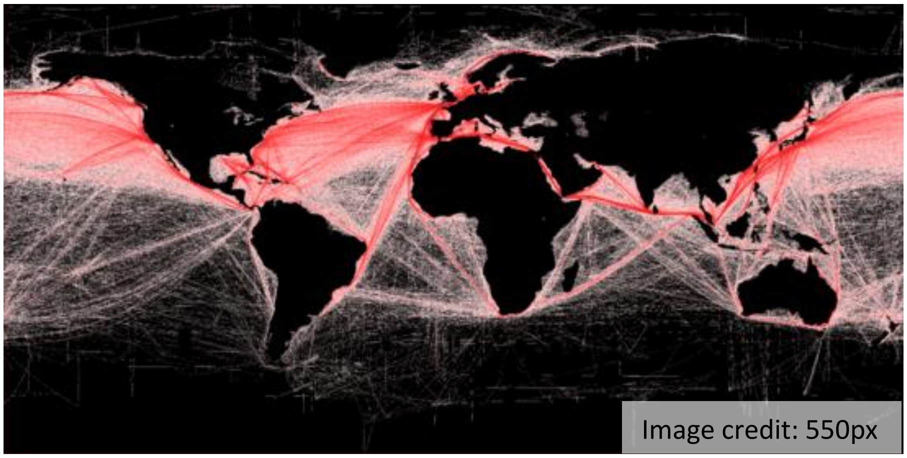

Image credit: 550px

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 (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, 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 16-2. 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).

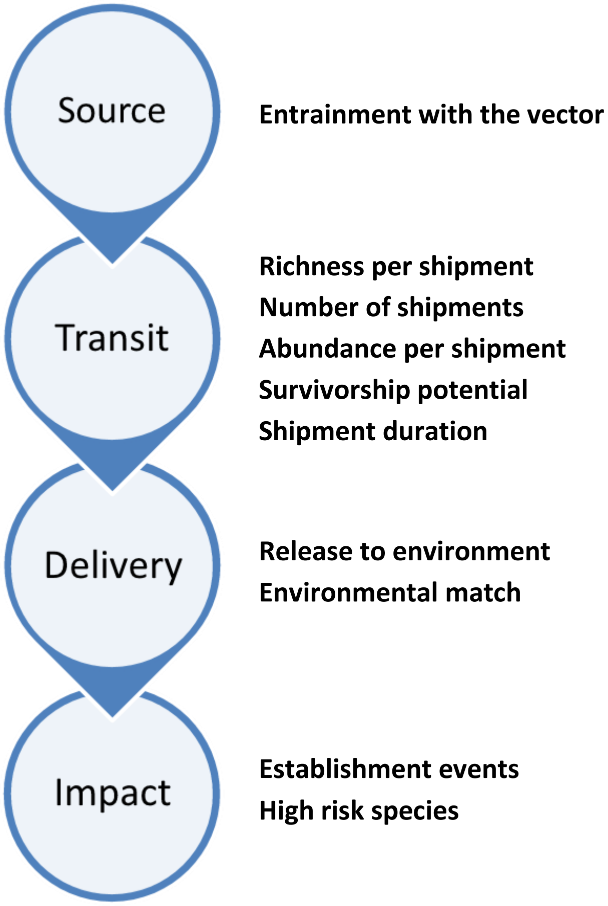

Figure 16-1. Invasion flow diagram showing the stages of the invasion process (Source, Transit, Delivery and Impact) and the component variables (adapted from Williams et al. 2013; COST 2013).

Table 16-1. Scoring guide to variables used in vector risk assessment (adapted from California Ocean Science Trust 2013)

Variable	Definitions	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 knowledge of the diversity of the species in the region 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 of Japan in 2015 and 2016 by JANUS and colleagues (see Chapter 8). The total species richness identified across all three locations was 95 species (or morphospecies). The final list of species found in each survey is shown in 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 in 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 shows that the available species diversity is substantial. Therefore, the JTMD vector score for the cumulative species richness variable is *High* (>1000 species).

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

Vector Comparison

As a proxy for number of available species for other vectors, the number of source countries is used to compare between vectors. All the other vectors of transport have more than a single source country. Commercial shipping to the USA and Canada comes 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*.

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 16-4).

Country	Destination Port	Ecoregion	Origin Port Countries
USA	Valdez, AK	Gulf of Alaska	21
USA	Seward, AK	Gulf of Alaska	19
USA	Anchorage, AK	Gulf of Alaska	18
USA	Kodiak, AK	Gulf of Alaska	15
USA	Sitka, AK	North American Pacific Fjordland	
Canada	Prince Rupert	North American Pacific Fjordland	65
Canada	Kitimat	North American Pacific Fjordland	34
Canada	Stewart	North American Pacific Fjordland	15
USA	Juneau, AK	North American Pacific Fjordland	21
USA	Ketchikan, AK	North American Pacific Fjordland	20
USA	Astoria, OR	Oregon, Washington, Vancouver Coast and Shelf	99
USA	Portland, OR	Oregon, Washington, Vancouver Coast and Shelf	73
USA	Newport, OR	Oregon, Washington, Vancouver Coast and Shelf	71
USA	Coos Bay, OR	Oregon, Washington, Vancouver Coast and Shelf	21
USA	San Francisco, CA	Northern California	146
USA	Sacramento, CA	Northern California	23
USA	Honolulu, HI	Hawaii	118
USA	Hilo, HI	Hawaii	19
USA	Kailua-Kona, HI	Hawaii	12

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 7-10). In total, 650 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 Misawa

1 dock and this item had 131 invertebrate and algae species. The data is 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 (650 items) was 316: 233 invertebrates, 80 algae and 2 fish species (see Chapters 7 and 9).

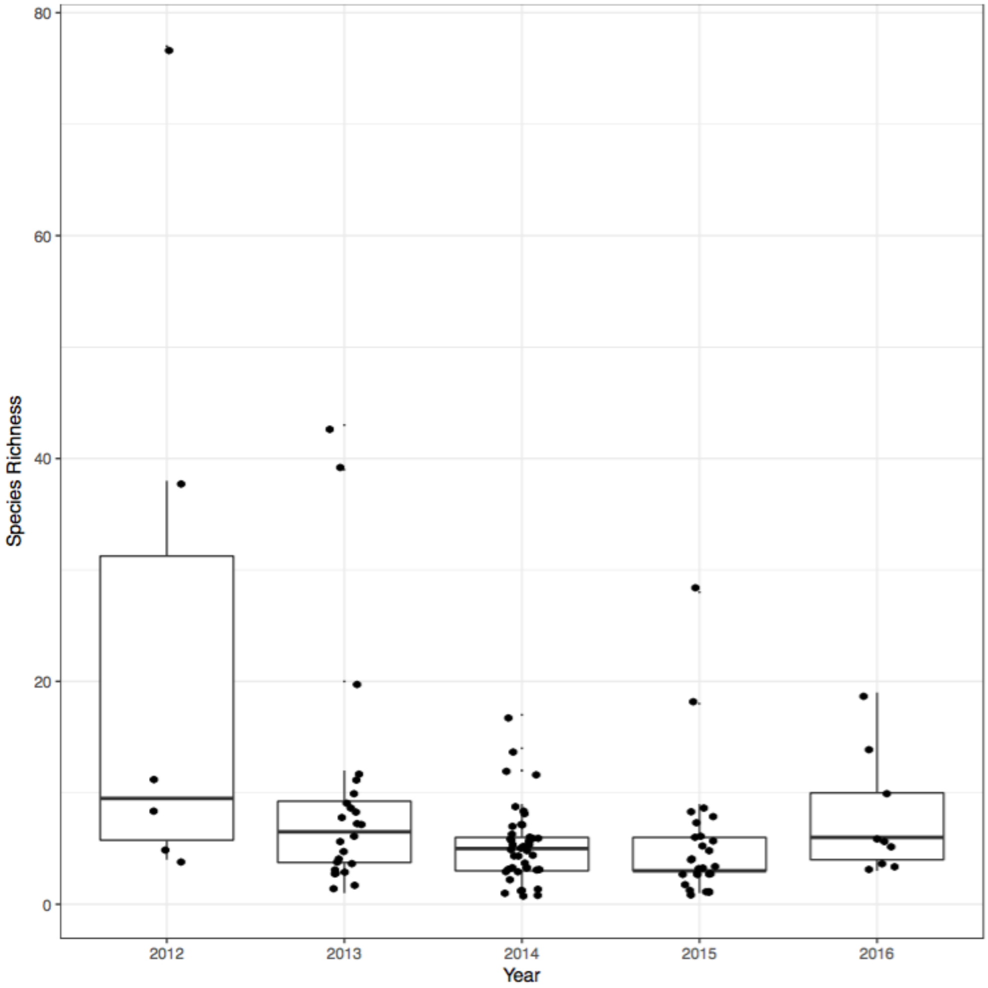

Figure 16-2. Box-and-whiskers plot of invertebrate species richness per item on sampled JTMD items (Category 1 items only). The box encloses the 1st and 3rd quartiles and the black dots represent individual debris items. The bold line is the median species richness.

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 Category 1 and others that were more haphazard Category 2 samples. 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 (Category 1 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 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.

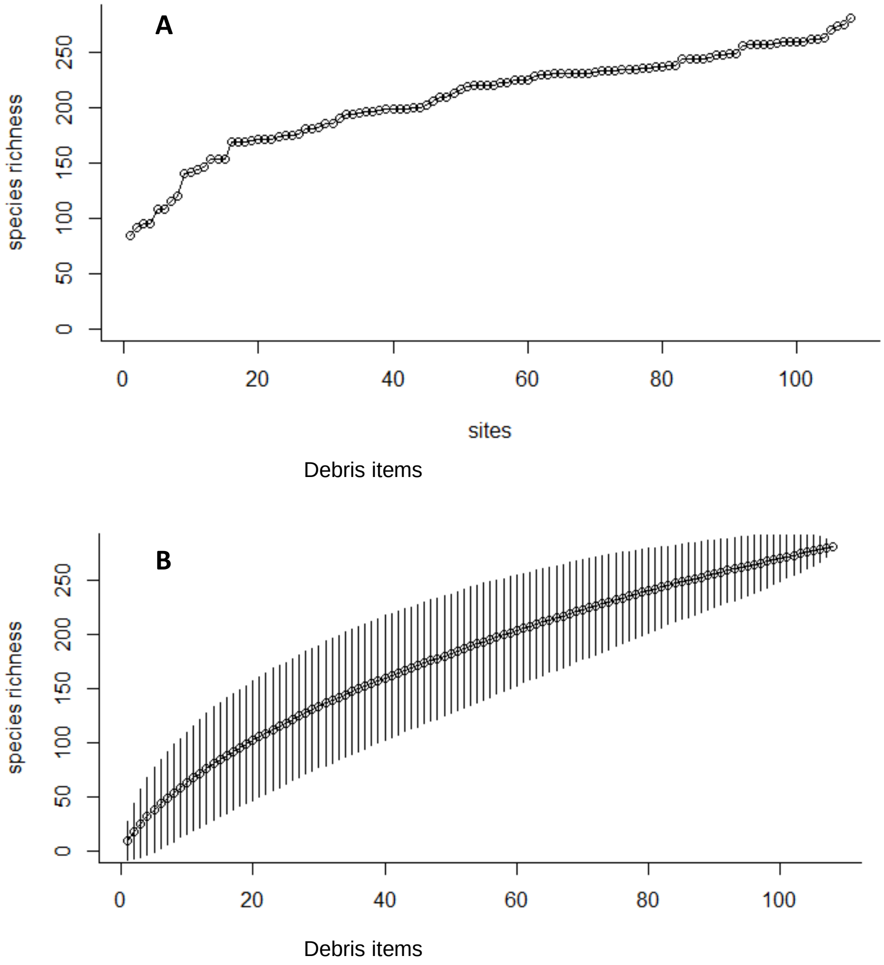

Figure 16-3. A) Species accumulation curve and B) rarefaction plot of the species richness for 108 Category 1 JTMD items.

Vector Comparison

From the available data on ballast water, ships originating from Japan sampled in Coos Bay, Oregon, USA 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 176 zooplankton taxa were identified from the ballast water samples of 70 vessels (DiBacco et al. 2011). Casas-Monroy et al. (2014) identified 184 zooplankton and phytoplankton taxa from 70 vessels arriving at Port of Vancouver, Canada. Levings et al. (2004) sampled 15 ships in Vancouver Harbour, Canada 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 six 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 five 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 shipments (Williams et al. 2013) and the score is ranked *Medium*.

Number of shipments

The JTMD Vector

The number of shipments arriving at 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 North American and Hawaiian coastlines is difficult to estimate, we have several data source to use in the qualitative ranking of this variable. The original estimate from the Government of Japan suggests 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 650 objects were registered in the JTMD biofouling database (see Chapter 7 for rationale). Reports to the NOAA disaster debris reporting system totaled more than 1600 reports, 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 2012-2015 was almost 100,000 (see Chapter 3). Modelling results estimated that 1000 small boats were lost to the North Pacific with the tsunami and that 300-500 may still be floating in the North Pacific (see Chapter 2).

Table 16-4. NOAA Disaster debris reports by ecoregion and whether they were formally confirmed as JTMD (updated April 2016).

Ecoregion name	**Count**	**Confirmed JTMD**
Eastern Bering Sea	3	0
Aleutian Islands	1	0
Gulf of Alaska	78	4
North American Pacific 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
Grand Total	**1627**	60

Based on this evidence, the number of shipments associated with JTMD is ranked *High*, more than 1000 shipments arrived on the 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 to major ports in North America on an annual basis. Casas-Monroy et al. (2014) reported 1488 international ballast water discharge events for vessels arriving to 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 are both ranked *High* (> 1000). Aquaculture shipments were ranked *Medium* (100 - 1000) 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. Abundance was not recorded systematically for all debris items but 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, there were hundreds of individuals on the sampled JTMD items (see Chapter 11). Based on this evidence, the score for abundance per shipment for the JTMD vector is *Low* (< 1000).

Photo credit: CBC

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 to Vancouver Harbour to be 1.8×10^3 and 1.81×10^5, respectively. Ships arriving into Vancouver Harbour, Canada had a total of 3.7×10^4 organisms in a single ballast water sample (Levings et al. 2004) although data was 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 raked 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 is 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/Hawaii. A comparison between the species identified from fouling panels deployed in the Tohoku region of Japan 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 (Chapters 7-8).

Differences in growth and survival of model species, such as *Mytilus*, suggest that the voyage duration and route had some effect on 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. Therefore, we suggest that the survival of JTMD organisms is scored *Medium* (between 5 – 95% survival).

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, region, 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 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 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%).


Photo credit: Nicolas Cegalerba

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 16-4, upper panel). 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 16-4, lower panel). Even the highest windage items took months to reach the shores of the eastern Pacific. Therefore, JTMD is ranked *Low* (> 2 weeks) as all voyages lasted longer than 2 weeks.

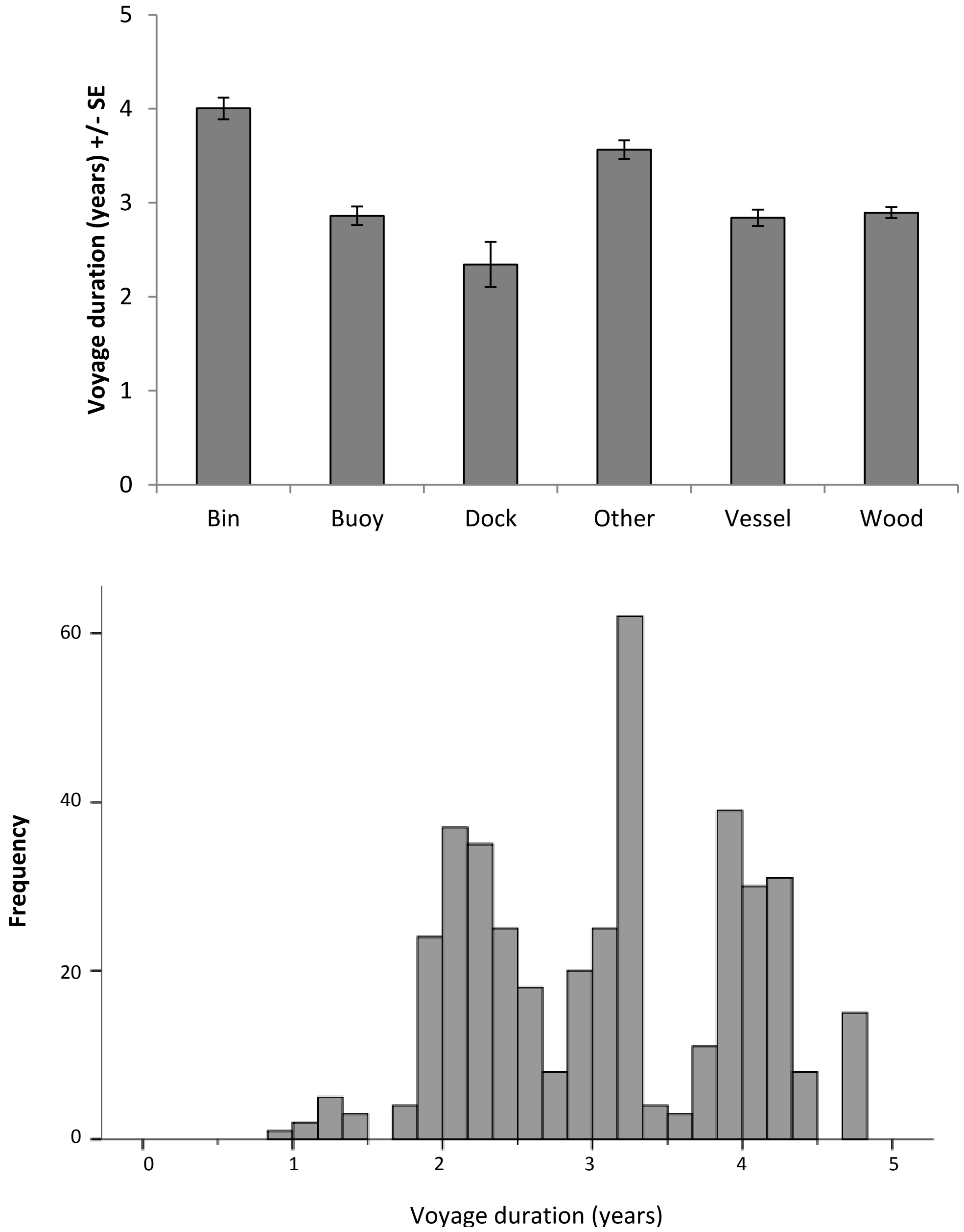

Figure 16-4. Voyage duration (years) for (upper panel) all debris items and (lower panel) JTMD item types.

Vector Comparison

Ballast water studies of transoceanic voyages from Japan to Coos Bay, Oregon 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 – 48 hours (Williams et al. 2013) and are given a score of *High* (≤ 1 day).

Delivery

Release to environment

Released to or in contact with 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 or associated with JTMD are already immersed in the environment and do not require a release event to occur. Additionally, the landing of debris on the shoreline 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%).

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 therefore 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 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 the 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 eco-region 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.

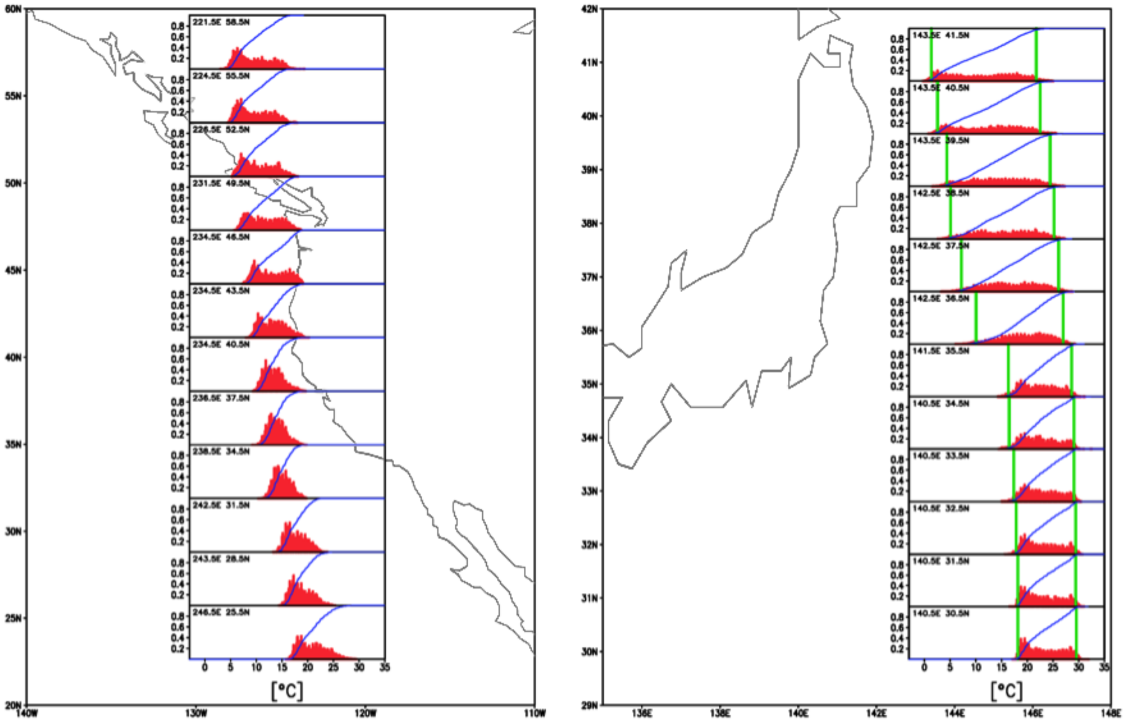

Figure 16-5. Probability density function (PDF; red bars) of sea surface temperature (SST) at different locations along (left) the east coast of Japan and (right) the west coast of North America, calculated from the AMSR satellite data. Blue lines are cumulative PDFs and green bars indicate SST limits after removing outliers.

The cumulative probability distributions for SST for the west coast of North America, north of 30°N, range from a 0.3 – 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 reduced environmental match. However, subtropical species, such as the striped beakfish, associated with JTMD could have been picked by JTMD in the Kuroshio Extension and these could have a higher match with sea surface temperatures in Hawaii (Figure 16-8). The score for environmental match for JTMD is therefore *Medium* (5-95%).

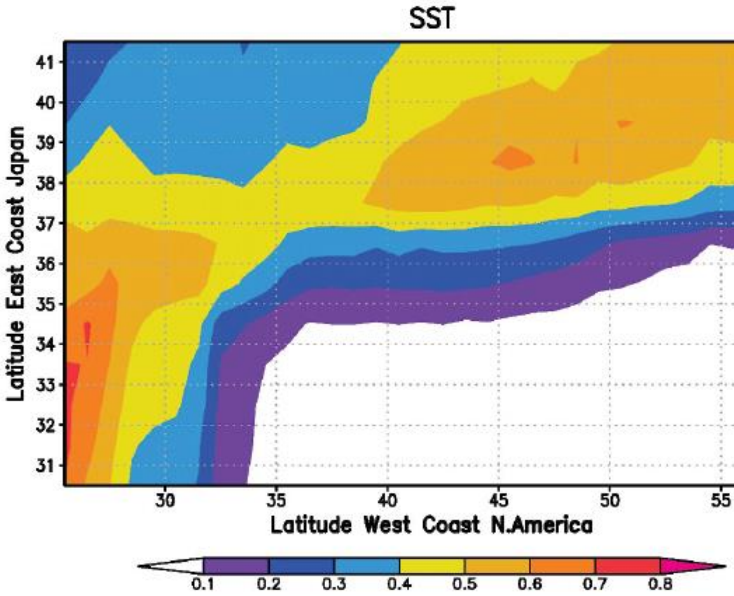

Figure 16-6. Cumulative probability distribution match for sea surface temperature (SST) range between east coast of Japan and west coast of North America.

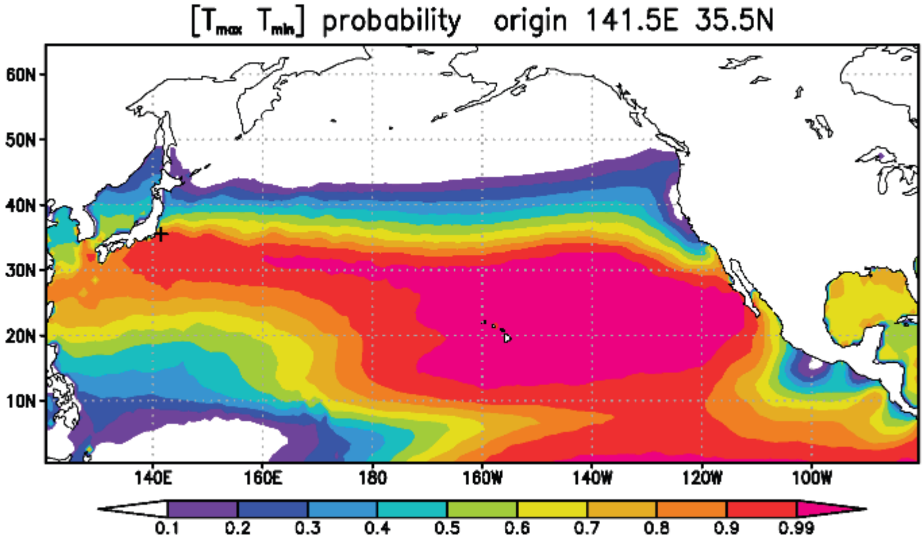

Figure 16-7. Degree of the sea surface temperature (SST) match with the climatology at select southern location east of Japan (marked with cross), calculated using AMSR satellite data.

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. Therefore, aquaculture 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

High risk species associated with JTMD

The research on the risk of JTMD began with identifying species associated with arriving JTMD (see Chapters 7-10). 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, reproductive and growth strategies for those species identified on JTMD (Appendix 12-2). Using 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 *Mytilus galloprovincialis* carried a hydroid parasite, *Eutima*, on JTMD objects, a parasite that 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 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 are unknown. Some of these species have traits and characteristics that are similar to other species with known invasion history (see Chapter 12). 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.

Species community associated with JTMD

Of the almost 300 species sampled from JTMD items, 21 species have also been 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 four species in common (Bonnot 1935; Kincaid 1947) and ballast water had four species in common with JTMD (Carlton and Geller 1993; DiBacco et al. 2011; Williams et al. 1988). 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).

While 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.

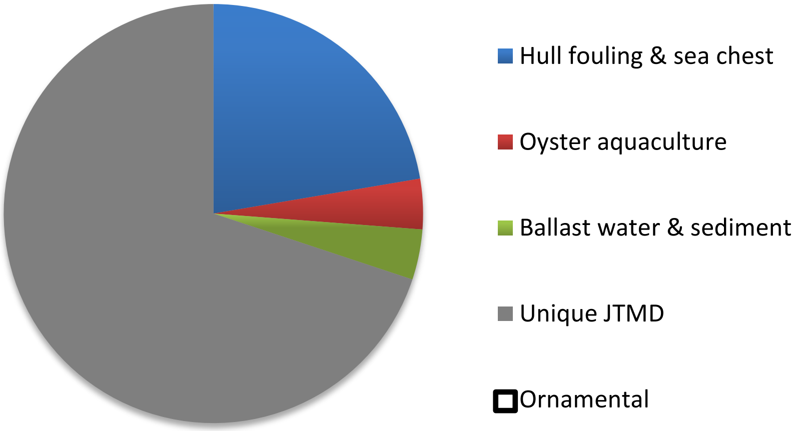

Figure 16-8. Community similarities between JTMD and other vectors: the percentage of genera recorded from each vector (hull fouling, oyster aquaculture, ballast water) that match that recorded from JTMD. Note that the ornamental vector had no genus or species in common with that from JTMD.

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

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 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 have indicated that some 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.

Photo credit: Hideaki Maki

While we have conducted field and genetic surveys to detect new invasions, the sheer length of coastline and diversity of habitats would be near 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 western North America and synthesized data in National Exotic Marine and Estuarine Species Information System (NEMESIS) databases through 2015. This served to evaluate the status of species detected in baseline surveys (above) and as well as other species known to occur in North America. Over 50% of marine and estuarine NIS reported in western North America also occur in Japan, when considering free-living invertebrates and algae, with roughly 30% native to Japan (Figure 16-8). 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 16-9) (Ruiz et al. 2015).

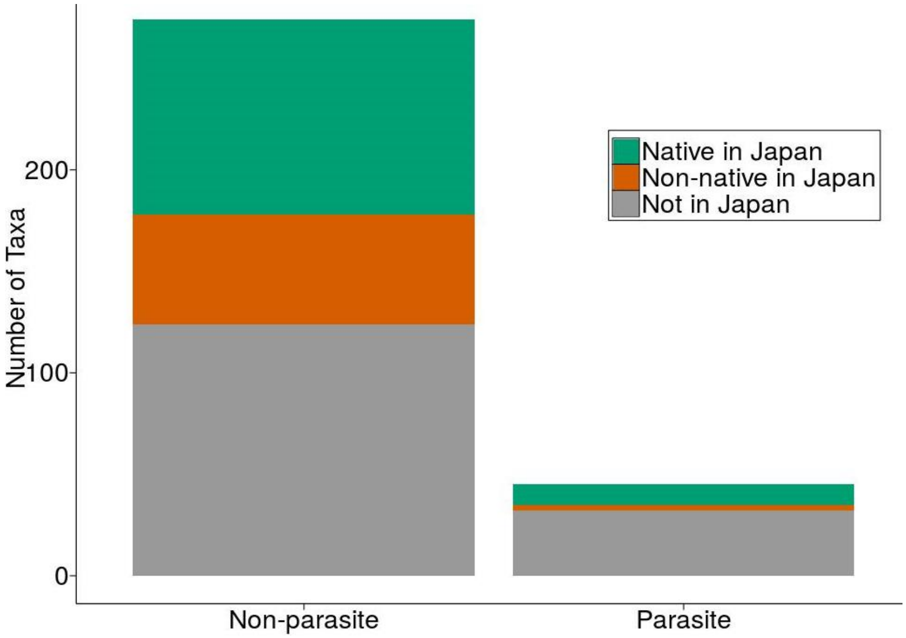

Figure 16-9. Total number of NIS reported for marine end estuarine habitats of western North America. The figure indicates the number of NIS for invertebrates and algae (excluding vertebrates and vascular plants), for each free-living species and parasite/commensal species. Color-coding indicates the number of NIS considered (a) native to Japan, (b) occur in Japan as introduced (NIS) or cryptogenic, or (c) not reported to occur in Japan. Data synthesis from NEMESIS (2003).

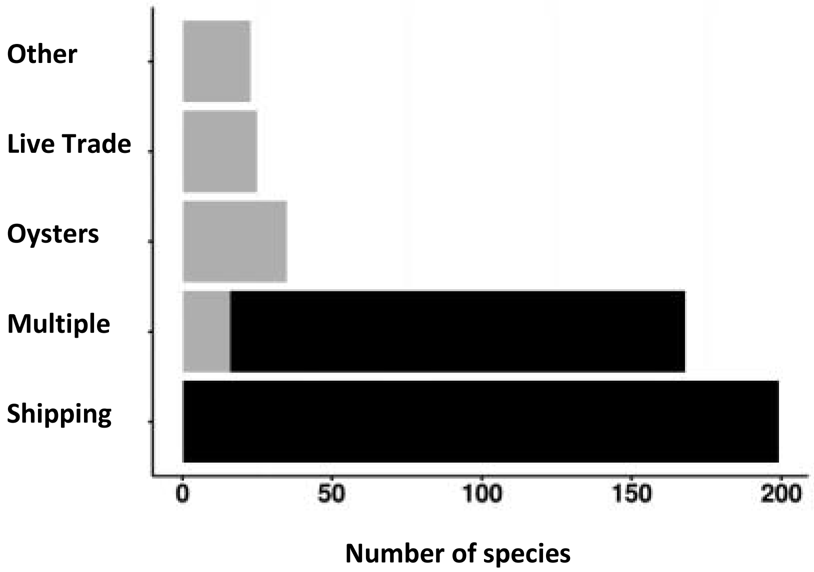

Figure 16-10. Vector strength for established NIS in North America. Shown are the numbers of NIS (invertebrates and algae) attributed to coarse vector categories through 2010, based on the initial introduction to North America; black bar indicates the number for which shipping is a sole or possible vector. “Multiple” refers to established NIS for which a single vector could not be definitively assigned. Figure adapted from Ruiz et al. (2015).

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, species richness, and abundance associated with JTMD items have all rapidly declined over the 5 years of study. The qualitative risk assessment conducted here shows that JTMD is most similar to hull fouling of commercial shipping. This assessment shows that the JTMD vector ranks Low on three 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). In contrast, all other marine vectors assessed here 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 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. 2010; 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	High	Low	High	Low	Low	Medium	High	Medium
Hull fouling	High	Medium	High	Medium	Medium	Medium	High	High
Ballast water	High	High	High	High	Medium	Medium	Medium	High
Ornamental	High	High	High	High	Medium	High	Low	Low
Aquaculture	High	Low	Medium	High	Medium	High	High	High
Historical aquaculture	High	Medium	Low	High	Medium	High	High	High
Historical ballast water	High	High	High	High	Medium	Medium	Medium	High

The JTMD vector is most similar in risk to hull fouling (Table 16-5; Figure 16-10). Both vectors transport adult and sessile fouling organisms in fouling communities, have high release to environment probabilities, and 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 vectors examined, with some items spending more than six 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) *versus* typical commercial vessel speeds of 20 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, (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.

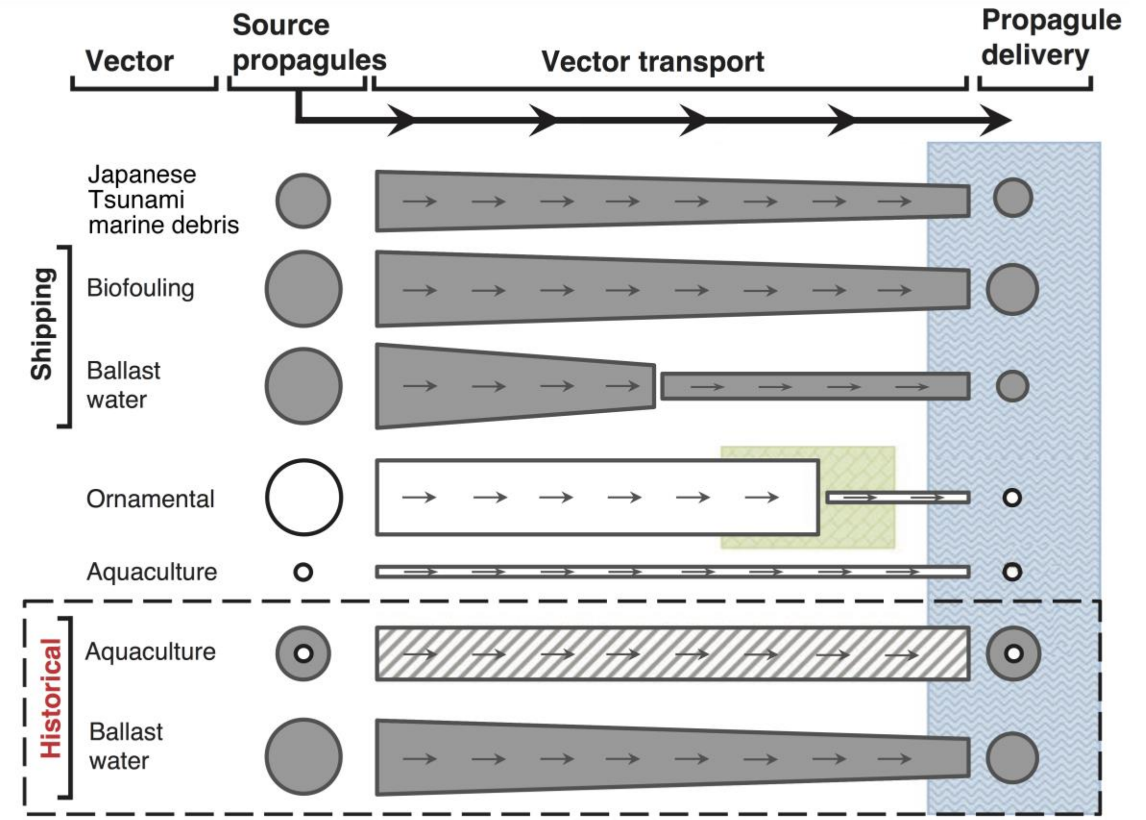

Figure 16-11. Comparison of Japanese Tsunami Marine Debris (JTMD) and eight other maritime vectors. Eight vectors are compared across the relative size of the source propagule pools (the circles on the left), typical transit processes (the polygons in the middle section), and relative inocula sizes during 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 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 William et al. (2013).

Remarkably, JTMD with living Japanese species from the Tohoku coast continues to arrive in North America and the Hawaiian Islands six 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 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.

From this comparison, we conclude that JTMD is comparatively lower risk than other North Pacific vectors. No introductions have yet been detected in any 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 the 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 ADRIFT and compare the role that JTMD played if a new introduction were to occur.

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Appendices

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	100-1000 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	100-1000 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%

Chapter 17: Project summary and legacy products

The Great East Japan Earthquake on March 11, 2011 was devastating for the people of Japan. In addition to the 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 effects of this debris (so-called Japanese Tsunami Marine Debris or JTMD), especially those related to non-indigenous species (NIS), on ecosystem structure and function, the coastlines, and communities of the Pacific coast of North America and in Hawaii a PICES project, 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 Impact **F**rom **T**sunami), focused on three main research topics: (1) modeling movement of marine debris in the North Pacific, (2) surveillance and monitoring of JTMD landfall and accumulation, and (3) assessing risk from JMTD, including potential impacts from NIS, on coastal ecosystems in North America and Hawaii. Key findings and legacy products from this unique research project are highlighted here.

To characterize and forecast the propagation and destiny of JTMD, large-scale oceanographic modeling was employed that highlighted how it was necessary to consider the windage of different items as it affected their voyage duration and path. Additional model refinements allowed the characterization of oceanographic conditions along probable paths of individual JTMD items, which was critical to better understanding the fate of NIS being carried on JTMD.

As predicted, JTMD started arriving to coastal regions of North America and in Hawaii within a year of the Great Tsunami of 2011. This debris was detected at baseline marine debris monitoring sites where up to a 10-fold increase was noted. These observations are consistent with the spatial and temporal trends in disaster debris reports, shoreline debris surveys, and oceanographic modeling predictions, thereby confirming a substantial increase in debris influx to the shorelines of North America and Hawaii. In addition, systematic aerial 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 evaluation in these two regions providing an important baseline of marine debris, and complemented similar efforts conducted previously in Alaska. These products from the ADRIFT project are available online for others to use.

JTMD carried coastal Japanese organisms to the shorelines of Pacific North America and Hawaii. To date, more than 380 species of marine animals and plants have been detected on JTMD reaching North America since the summer of 2012, with new species still arriving more than six years later (spring of 2017). Thus, a substantial number of invertebrate and algal species, including many short-lived ones, rafting on JTMD were able to grow and reproduce during their multi-year journey through the relatively resource-limited North Pacific Ocean. The collection and processing of over 650 registered JTMD items produced more than 1,000 individual samples in museum-quality glass jars. Considerable curatorial effort was focused on establishing the JTMD Biodiversity Archives for long-term stewardship, so that future researchers will have access to this unique resource housed at the Royal British Columbia Museum in Victoria, Canada.

Detailed geographic, environmental, and life history information was compiled for more than 160 JTMD species that will be an important resource for improving our basic understanding of species transport, attributes related to invasion success, and can contribute to risk assessments. As part of the ADRIFT project, a screening level risk assessment tool (CMIST) was applied to species found on JTMD. This process identified a number of higher risk invasive species that may pose a threat to North American and Hawaiian ecosystems. 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 some of the assessed ecoregions, while others, like the shore crab *Hemigrapsus sanguineus* and the algae *Grateloupia turuturu*, have yet to invade the Pacific coast of North America. Although surveys of Pacific North American and Hawaiian coastlines have not detected any invasions attributable to the tsunami event, monitoring efforts should be continued in each of the affected ecoregions given the lag-time often noted for marine invasions. When compared to other marine vectors for invasive species, we concluded that JTMD is most similar to hull fouling and could be considered a lower risk given the unique, one-time nature of JTMD compared to the ongoing redistribution of species associated with commercial shipping and other invasion vectors.

The ADRIFT project produced a remarkable number of publications and legacy products. Two journal special issues are in production (the expected publication date is late 2017); papers focused on the taxonomy of the JTMD species will be published in *Aquatic Invasions*, and papers on modeling, surveillance, monitoring, ecology and risk of species will be published in *Marine Pollution Bulletin*. The following legacy products from the project are available to the public and scientific community:

PICES JTMD species database

About 650 debris items attributed to the Great Tsunami of 2011 have been intercepted thus far, and over 380 species of algae, invertebrates and fish have been identified associated with this JTMD. Many of the species encountered are native to Japan, and are not currently present in North America or Hawaii ecosystems. In order to better understand the potential risk of these species to North American and Hawaiian coastlines, information on the distribution, biology, ecology, life history traits and invasion history of these species was compiled by applying a standardized search protocol of online resources, databases, and scientific literature written in both English and Japanese.

The PICES-JTMD species database (http://invasions.si.edu/nemesis/jtmd/index.jsp) on the Smithsonian Institution online portal NEMESIS (National Exotic Marine and Estuarine Species Information System) provides comprehensive information on the invertebrate and algae species associated with debris originating from the 2011 Great East Japan Earthquake and Tsunami. The species included were identified from confirmed or suspected JTMD found on the coasts of

North America and Hawaii, but do not necessarily represent established populations of these species.

Each species record contains:

- Information on the biology, ecology, and effects (impacts);
- Global distribution maps of native and introduced range;
- Mechanisms (vectors) of introduction;
- History of introduction and spread;
- References to available literature.

JTMD

Japanese Tsuanmi Marine Debris database

Welcome to the JTMD (Japanese Tsunami Marine Debris) species database

Overview

The JTMD species database provides information on species of invertebrate and algae associated with debris originating from the 2011 Great East Japan Earthquake and Tsunami.

Each species record contains:

- Information on the biology, ecology, and effects (impacts);
- Global distribution maps of native and introduced range;
- Mechanisms (vectors) of introduction;
- History of introduction and spread;
- References to available literature

Scope

The JTMD species database is limited to species identified in association with Japanese tsunami debris items. The species listed were identified from confirmed JTMD found on the coasts of North America and Hawaii, but do not necessarily represent established populations of these species.

Royal British Columbia Museum JTMD specimen collection archive

With over 650 registered JTMD items producing more than 1,000 individual samples in museum-quality glass jars, considerable curatorial effort was focused on establishing the JTMD Biodiversity Archives for long-term stewardship. These archives will allow future researchers to have access to this unique resource, especially with the undoubted advance of new analytical techniques in years to come.

The Royal British Columbia Museum (RBCM), through its Collections Committee, has confirmed acceptance of the unique biological sample collection of biota (marine invertebrates) recovered from JTMD (http://www.royalbcmuseum.bc.ca/collections/natural-history/invertebrate-zoology; contact: Dr. Henry Choong (Curator, Invertebrate Zoology; hchoong@royalbcmuseum.bc.ca).

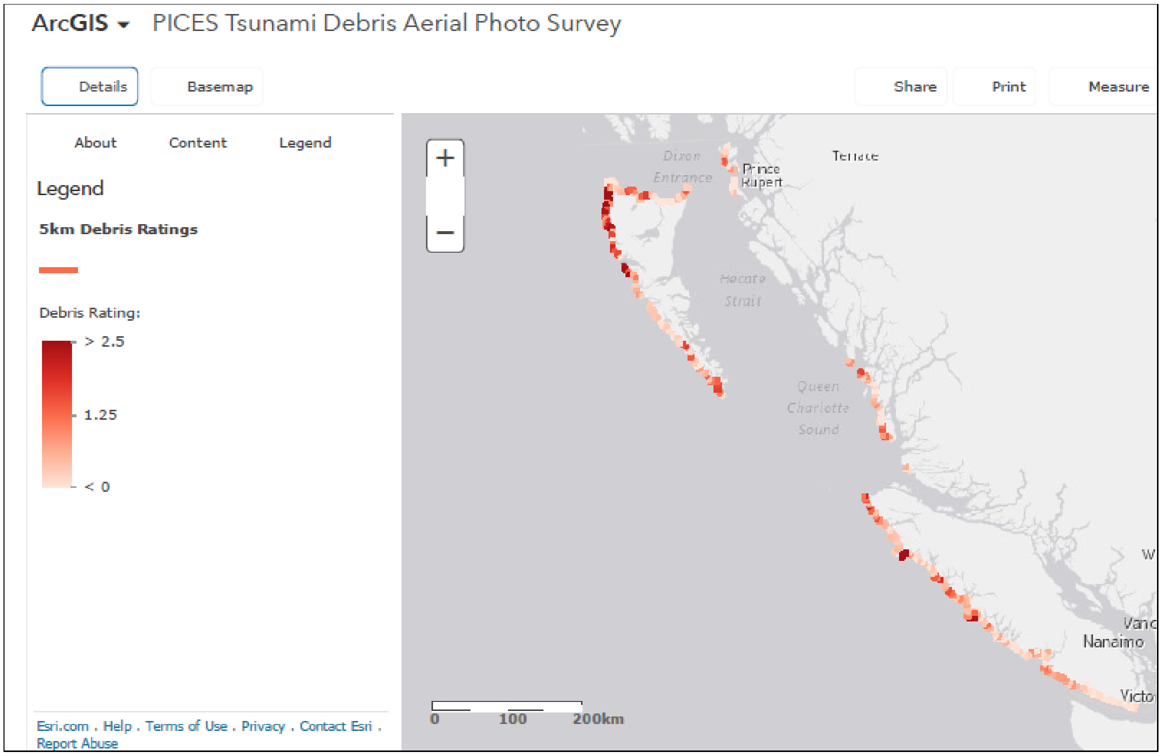
JTMD algae identification guides

The Identification Guide provides information for morphologically identifying some of the most prominent species of seaweeds found on JTMD and is available online through Kobe University (http://www.research.kobe-u.ac.jp/rcis-kurcis/KURCIS/FieldGuide2017may14LR.pdf).

Morphological documentation on benthic marine algae on JTMD (Part 1: Introduction and the Brown Algae; Part 2: The Green Algae and Cyanobacteria; and Part 3: The Red Algae) will be available through Oregon State University's online library (https://ir.library.oregonstate.edu/) in July 2017.

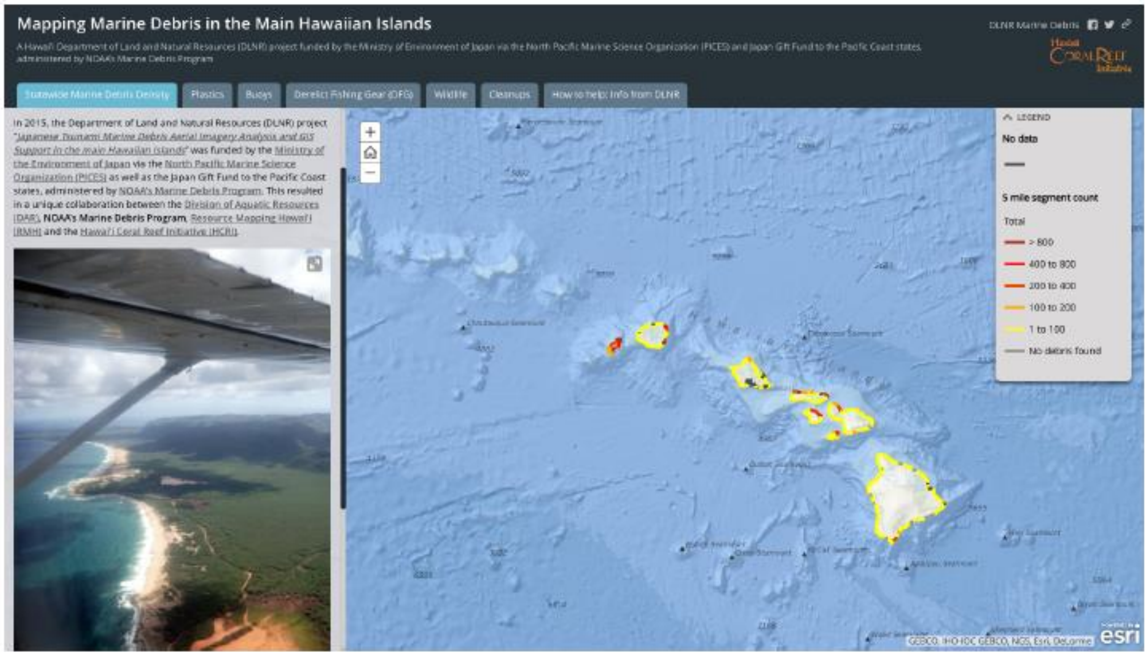
BC aerial survey mapping portal

ADRIFT-funded aerial surveys of the entire exposed outer coast (more than 1,500 km) of British Columbia (BC) were conducted in 2014 and 2015 to evaluate debris accumulation in this area. Additionally, funding provided by the Japan Tsunami Gift Fund, administered by the BC Ministry of Environment, was used for GIS analysis of the tagged photographs. All photographs, debris ranking segments and maps are now available to the public through an online mapping portal designed and hosted by the BC Provincial Government (PICES Tsunami Debris Aerial Photo Survey – http://www.arcgis.com/home/webmap/viewer.html?webmap=3c5fb88b7f3f4d97974615acad67af3e).



Hawai'i aerial survey mapping portal

To identify and locate marine debris accumulation areas, aerial surveys of the eight main Hawaiian Islands (~2,000 km of coastlines), coordinated by Hawaii's Department of Land and Natural Resources (DLNR), 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 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 aerial surveys are available through ArcGIS Story Map (http://arcg.is/29tjSqk), and can also be viewed online or downloaded for public use through the State of Hawaii Office of Planning Service Directory at http://geodata.hawaii.gov/arcgis/rest/services/SoH_Imagery/Coastal_2015/ImageServer. Requests for proper accreditation as well as watermarks are present on all public materials, as directed by PICES and DLNR.



Mapping Marine Debris in the Main Hawaiian Islands

A Hawai'i 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

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" was funded by the Ministry of the Environment of Japan via the North Pacific Marine Science Organization (PICES) as well as the Japan Gift Fund to the Pacific Coast states, administered by NOAA's Marine Debris Program. This resulted in a unique collaboration between the Division of Aquatic Resources (DAR), **NOAA's Marine Debris Program**, Resource Mapping Hawai'i (RMH) and the Hawai'i Coral Reef Initiative (HCRI).

Chapter 18: Publications and presentations

Publications

THEME I – Movement of debris

Clarke Murray, C., Lippiatt, S., Maximenko, N., and Wallace, N. 2017. The influx of marine debris from the 2011 Great Japan Tsunami to North American shorelines. *Marine Pollution Bulletin special issue*. 17 pp.

Kamachi, M. 2016. Chapter 2: Data Assimilation – An Informal Introduction to Global Optimization in the Ocean, pp. 35-56 *in* Series Optimization Modeling 5 *edited by* K. Murota, A. Ikegami, and T. Tsuchiya, The Operations Research Society of Japan (supervision), Kindai-Kagaku Sya (in Japanese).

Kamachi, M., Daniel, P., Tolman, H., Maximenko, N., and Kawamura, H. 2017. Chapter 28: Modelling and predictions of contaminants at sea *in* The Sea vol.17: The Science of Ocean Prediction *edited by* N. Pinardi, P.F.J. Lermusiaux, and K.H. Brink, Yale University Press (under second revision).

Maximenko, N., Centurioni, L., Chao, Y., Dohan, K., Galgani, F., Hardesty, B.D., Law, K.L., Moller, D., van Sebille, E., Wilcox, C. 2016. Remote sensing of marine debris, White Paper for the Earth Science and Applications from Space Decadal Survey, RFI1.

Maximenko, N., Hafner, J., Kamachi, M., and MacFadyen, A. 2017. Modeling paths and fate of marine debris from the 2011 Great Tohoku Tsunami, Marine Pollution Bulletin special issue.

Maximenko, N., MacFadyen, A., and Kamachi, M. 2015. Modeling drift of marine debris from the Great Tohoku tsunami, *PICES Press,* Summer 2015**,** Vol. 23, No. 2, pp. 32-36.

Maximenko, N. et al. (41 co-author and 2 supporters). 2016: Remote sensing of marine debris to study dynamics, balances and trends, White Paper for the Earth Science and Applications from Space Decadal Survey, RFI2.

THEME II – Monitoring and surveillance

DLNR Division of Aquatics. 2016. Japanese Tsunami Marine Debris Aerial Imagery Analysis and GIS Support Final Report. http://dlnr.hawaii.gov/dar/reports/. 96 pp.

Isobe, A., Kako, S., Kataoka, T., Iwasaki, S., Plybon, C., and Murphy, T.A. 2017. Webcam monitoring and modeling of Japanese tsunami marine debris washed ashore on the western coast of the North America. *PICES Press* 25(1): 32-35.

Kako, K., Isobe, A., Kataoka, T., Yufu, K., Sugizono, S., Plybon, C., and Murphy, T.A. Sequential webcam monitoring and modeling of Marine debris abundance on a beach of the western US coast. *Marine Pollution Bulletin* special issue.

Kataoka, T., Clarke Murray, C., and Isobe, A. Quantification of marine macro-debris abundance around Vancouver Island, Canada, based on archived aerial photographs processes by the projective transformation. *Marine Pollution Bulletin* special issue.

THEME III – Rafting of species

Special Issue of *Aquatic Invasions* (2017), with James T. Carlton and Amy E. Fowler as Co-Editors. These papers include:

Carlton, J.T., Chapman, J.W., Breitenstein, R., Otani, M. Transoceanic Dispersal of Coastal Barnacles (Crustacea: Cirripedia) on Japanese Tsunami Marine Debris.

Carlton, J.T., Chapman, J.W., Geller, J.A., Miller, J., Ruiz, G.A., Carlton, D.A., McCuller, M.I., Steves, B. Japanese marine amphipod, isopod, and tanaid crustaceans arriving in North America on terrestrial and marine debris generated by the 2011 Japanese Tsunami.

Carlton, J.T., Chapman, J.W., Geller, J., Miller, J.A., Ruiz, G.M., Carlton, D.A., McCuller, M.I., Treneman, N., Lewis, R., Bilderback, D., Harris, L. Introduction to Special Issue: Biological and ecological studies of Japanese Tsunami Marine Debris.

Choong, H., Calder, D., Carlton, J.T. Hydrozoa.

Cordell, J.R.. Harpacticoid copepods associated with Japanese tsunami debris along the Pacific coast of North America and Hawaii.

Craig, M., Burke, J., Clifford, K., Mochon-Collura, E., Chapman, J., and Hyde, J.R. Trans-Pacific Rafting on Tsunami Associated Debris by the Japanese Yellowtail Jack, Seriola aureovittata (Pisces: Carangidae).

Eernisse, D., Draeger, A., Pilgrim, E. Polyplacophora (Chitons).

Eernisse, D., Pilgrim, E. Patellidae (Limpets).

Elvin, D., Carlton, J.T. Porifera collected from Japanese Tsunami Marine Debris on the Northwest coast of North America.

Finger, K. Tsunami-generated rafting of Foraminifera across the North Pacific Ocean.

Hansen, G.I., Hanyuda, T., and Kawai, H. Marine algae carried across the North Pacific on Japanese Tsunami Marine Debris (JTMD) and their invasion threat to the coasts of Oregon and Washington.

McCuller, M. and Carlton, J.T. Transoceanic rafting of Bryozoa across the North Pacific Ocean on Japanese tsunami marine debris, with the description of a new species of Bugula (Cheilostomatida, Bugulidae).

Ta, N., Miller, J.A., Chapman, J.W., Calvanese, T., Miller-Morgan, T., Clifford, K., Mochon-Collura, E., Carlton, J.T. The Western Pacific barred knifejaw, Oplegnathus fasciatus (Temminck & Schlegel, 1844) (Pisces: Oplegnathidae) on the Pacific coast of North America.

Tanaka, H., Yasuhara, M., Carlton, J.T. Transoceanic transportation of living marine Ostracoda (Crustacea) by the tsunami of the 2011 Tohoku Earthquake.

Therriault, T.W., Hodes, V., Lowe, G., Norgard, T., Abbott, C., Yakimishyn, J., Geller, J., Carlton, J.T. A Case History of Transoceanic Dispersal: The Korean Mussel (Mytilus coruscus) (Bivalvia: Mytilidae).

Treneman, N.C., Borges, L.M.S., Shipway, J.R., Raupach, M.J., Altermark, B., Carlton, J.T. A molecular phylogeny of shipworms (Bivalvia: Teredinidae) from Japanese Tsunami Marine Debris.

Treneman, N.C., Carlton, J.T., Borges, L.M.S., Shipway, J.R., Raupach, M.J., Altermark, B. Diversity and abundance of shipworms (Bivalvia: Teredinidae) in woody debris generated by the 2011 Japanese Earthquake and Tsunami.

West, J.A., Hansen, G.I., Hanyuda, T., and Zuccarello, G.C. 2016. Flora of drift plastics: a new red algal genus, *Tsunamia transpacifica* (Stylonematophyceae) from Japanese tsunami debris in the northeast Pacific Ocean. *Algae* 31 (4): 289-301. http://www.e-algae.org/

In preparation

Carlton, J.T., Chapman, J.W., Geller, J.A., Miller, J., Ruiz, G.A., Carlton, D.A., McCuller, M.I., Steves, B. Tsunamigenic Megarafting: Implications for Marine Biogeography and Transoceanic Species Dispersal [Overview paper]

Chapman, J.W., et al. Colonization and Self-Recruitment of a Marine Intertidal Japanese Fly on Rafted Marine Debris Crossing the North Pacific Ocean.

Hansen, G.I., Hanyuda, T., Kawai, H. (March 2017). An illustrated guide to the most invasive marine algal species on Japanese Tsunami Marine Debris.

Hanyuda, T., Kawai, H., and Hansen, G.I. (To be submitted in early 2017). A comparative molecular study of seaweed species on Japanese Tsunami Marine Debris (JTMD) that were present in both the NE and NW Pacific before the tsunami.

Hanyuda, T., Kawai, H., Hansen, G.I. (To be submitted in February 2017). Genetic identifications of macroalgae species on Japanese Tsunami Marine Debris (JTMD) and their genetic comparisons with wild populations in Northeastern Pacific coasts. Marine Pollution Bulletin, Special Issue

Treneman, N.C., Carlton, J.T., Borges, L.M.S., Shipway, J.R., Raupach, M.J., Altermark, B. Description of a new species of Western North Pacific shipworm in the genus Psiloteredo.

Presentations

List of all presentations associated with the 3-year project

THEME I – Movement of debris

Clarke Murray, C., Lippiatt, S., and Maximenko, N. The influx of marine debris to North American shorelines after the Great Tsunami of 2011. PICES Annual Meeting, 25 Years of PICES: Celebrating the Past, Imagining the Future, San Diego, CA, Nov 2–13, 2016.

Hafner, J., Maximenko, N., and Speidel, G. Transport of marine debris from the 2011 tsunami in Japan: model simulations and observational evidence. PICES 2014 Annual Meeting, Yeosu, South Korea, October 20-24, 2014.

Hafner, J., Maximenko, N., and Speidel, G. Observational support for the IPRC model simulations of marine debris transport from the 2011 Japan tsunami. 26th IUGG 2015 General Assembly, Prague, Czech Rep., June 22-July 2, 2015.

Hafner, J., Maximenko, N., and Speidel, G. Transport of JTMD in IPRC model simulations and observations. 2015 Hilo Symposium on Marine Debris & Tsunami Driftage, Hilo, Hawaii, December 3, 2015.

Hafner, J., Maximenko, N., Speidel, G., and Wang, K.L. ‘Waves’ of tsunami debris: effect of the windage. Workshop on Mission Concepts for Marine Debris Sensing, Honolulu, Hawaii, January 19-21, 2016.

Hafner, J., Maximenko, N., Speidel, G., Wang, K.L. “Waves” of Tsunami debris in Hawaii: Effect of the windage. IPRC Annual Symposium, Honolulu, March 29, 2016.

Kamachi, M., Ishikawa, Y., Kawamura, H., Maximenko, N., Hafner, J., & MacFadyne, A. Ocean Modeling the Drift Simulation of Japan Tsunami Marine Debris (JTMD). Special Lecture Series for Graduate Students about Moe-PICES JTMD Project, at Tohoku University, May 19, 2017.

Kamachi, M., Ishikawa, Y., Kawamura, H., Maximenko, N., Hafner, J., & MacFadyne, A. Modeling the Drift of Japan Tsunami Marine Debris (JTMD): An Application of High Computing Simulation and Data Assimilation, Techno Ocean 2016, Kobe, 2016.

Kamachi, M., Kawamura, H., Ishikawa, Y., and Usui, N. Drift simulation of Japan Tsunami Marine Debris (JTMD) as an application of data assimilation. PICES Annual Meeting, 25 Years of PICES: Celebrating the Past, Imagining the Future, San Diego, CA, Nov 2–13, 2016.

Kamachi, M., Maximenko, N., Hafner, J., MacFadyne, A., Kawamura, H., & Ishikawa, Y. 2016. Modeling the Drift of Japan Tsunami Marine Debris (JTMD). The Moe-PICES JTMD Project Symposium, at Tokyo University of Marine Science and Technology, May 18, 2017.

Kamachi, M., Maximenko, N., Hafner, J., MacFadyne, A., Kawamura, H., & Ishikawa, Y. 2016. Modeling the Drift of Japan Tsunami Marine Debris (JTMD). Moe-PICES JTMD Symposium, at Sendai International Center, May 20, 2017.

MacFadyen, A., and Watabayashi, G. Trends in arrival and deposition of marine debris generated by the March 2011 Japan Tsunami on Eastern Pacific shorelines. PICES Annual Meeting, 25 Years of PICES: Celebrating the Past, Imagining the Future, San Diego, CA, Nov 2–13, 2016.

Marine debris working group, UNESCO/GESAMP, Paris, France, August 31 – September 2, 2015.

Maximenko, N. Ocean circulation and marine debris, Virtual lecture at the NIH Academic Center, May 6, 2015.

Maximenko, N. Modeling the drift of marine debris generated by the 2011 Tsunami in Japan. Oceania Regional Response Team Meeting, Ford Island, Pearl Harbor, Hawaii, September 17, 2015.

Maximenko, N. Surface currents and the motion of marine debris. The 2nd GlobCurrent User Training and Development Meeting, Brest, France, November 4-6, 2016. (pre-recorded presentation)

Maximenko, N. Presentation at the Vector Risk Assessment workshop, Burlington, Canada, January 10-12, 2017.

Maximenko, N. Ocean surface circulation: dynamical challenges, impacts and applications. Symposium on “Past, Present, Future of Predicting Ocean and Climate Variability", APL/University of Tokyo, January 26, 2017.

Maximenko, N. Ocean surface currents and applications to marine debris, Oceanography Seminar, University of Hawaii, February 16, 2017.

Maximenko, N. Marine debris research by the IPRC team, HI-MDAP Research Hui Workshop, Honolulu, USA, March 31, 2017.

Maximenko, N. The IPRC Marine Debris Project, Marine Litter Workshop, Barcelona, Spain, October 27-28, 2017.

Maximenko, N., and Hafner, J. Japan Tsunami Marine Debris Research by the IPRC/UH Team. PICES Working Group Meeting, Seattle, WA, July 29 – August 1, 2014.

Maximenko, N., Hafner, J., MacFdyen, A., and Kamachi, M. Predictability of marine debris motion, simulated with numerical models and diagnosed using oceanographic satellite data. Ocean Surface Topography Science Team Meeting, Hyatt Regency, Reston, Virginia, USA, October 20-23, 2015.

Maximenko, N., Hafner, J., MacFadyen, A., and Kamachi, M. Using disaster debris data to train dynamical models. Workshop on Mission Concepts for Marine Debris Sensing, Honolulu, Hawaii, January 19-21, 2016.

Maximenko, N., Hafner, J., MacFadyen, A., Kamachi, M., Clarke Murray, C., Carlton, J.T., Chao, Y., Moller , D. Calibration, validation and advanced applications of ocean drift models, forced with ocean satellite data, using marine debris reports from natural disasters. Ocean Surface Tomography Science Team Meeting, La Rochelle, France, October 31 - November 4, 2016.

Maximenko, N., Hafner, J., MacFadyen, A., Kamachi, M., and Speidel, G. Synthesis of numerical drift models and JTMD boat reports: first signs of quantitative consistency. 2015 Hilo Symposium on Marine Debris & Tsunami Driftage, Hilo, Hawaii, December 3, 2015.

Maximenko, N., Hafner, J., MacFadyen, A., Kamachi, M., and Clarke Murray, C. Using the data from accidents and natural disasters to improve marine debris modeling. 2016 Ocean Sciences Meeting, New Orleans, Louisiana, February 21-26, 2016.

Maximenko, N., Hafner, J., MacFadyen, A., Kamachi, M., and Speidel, G. Synthesis of marine debris modeling and observations: recent progress in understanding and applications. 2016 New Year Symposium on Marine Litter, Tokyo, Japan, January 23-24, 2016.

Maximenko, N., Hafner, J., Speidel, G. and Wang, K. Oceanography of marine litter. IPRC Annual Symposium, Honolulu, March 29, 2016.

Maximenko, N., MacFadyen, A., and Kamachi, M. Modeling the drift of marine debris generated by the 2011 tsunami in Japan. 42nd session of GESAMP, IOC-UNESCO Headquarters, Paris, France, August 31 to September 3, 2015. (poster)

Maximenko, N., MacFadyen, A., and Kamachi, M. Modeling the drift of marine debris generated by the 2011 tsunami in Japan. PICES Annual Meeting, 25 Years of PICES: Celebrating the Past, Imagining the Future, San Diego, CA, Nov 2–13, 2016.

Maximenko, N., MacFadyen, A., Kamachi, M., and Hafner, J. Modeling the drift of marine debris generated by the 2011 tsunami in Japan and synthesis with observations, ASLO Meeting, Honolulu, USA, February 26 – March 3, 2017.

Maximenko, N., MacFadyen, A., Kamachi, M., Hafner, J., Speidel, G., Curto, C., Usui, N., and Ishikawa, Y. Modeling studies in support of research on impact of alien species transported by marine debris from the 2011 Great Tohoku Tsunami in Japan. PICES MoE Project Science Team Meeting, Honolulu, Hawaii, March 16-18, 2015.

Moller, D., Maximenko, N., and Chao, Y. Remote sensing of marine debris. IGARRS, Beijing, China, July 10-15, 2016.

Speidel G., Maximenko, N., Hafner, J., Wang, K.L. The science behind the Japan tsunami marine debris in Hawaii. 2015 Hilo Symposium on Marine Debris & Tsunami Driftage, Hilo, Hawaii, December 3, 2015.

Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Sherman, P., Hardesty, B.D., van Franeker, J., Eriksen, M., Siegel, D., Galgani, F., and Law, K.L. Modelling the global distribution and risk of small floating plastic debris, 2016 Ocean Sciences Meeting, New Orleans, Louisiana, February 21-26, 2016.

THEME II – Arrival of debris

Isobe, A. An estimate of the tsunami-debris quantity washed ashore on the US and Canadian beaches, based on a webcam monitoring and a particle tracking model experiment. PICES annual meeting, San Diego, 9 Nov., 2017.

Kako, S. Sequential monitoring of marine debris washed ashore on a western US beach using a webcam system. PICES annual meeting, San Diego, 9 Nov., 2017.

Kako, S., Sugizono, S., Kataoka, T., Isobe, K.Y.A. Webcam monitoring of marine debris on the western coast of US. Annual Meeting of Japan Oceanographic Society, 16S25-12, Tokyo, Japan, 15 Mar. 2016. (In Japanese)

Kataoka, T. Accumulation of beach litter in Vancouver Island, Canada. PICES annual meeting, San Diego, 9 Nov., 2017.

Kataoka, T., Kako, S., Clarke Murray, C., Plybon, C., Murphy, T.A., Barnea, N., Hinata, H., Isobe, A. 2016. Techniques for quantifying the accumulation of marine debris on beaches. Workshop on Mission Concepts for Marine Debris Sensing, Honolulu, USA, 19-21 Jan. 2016.

Science Seminar “Remote monitoring of Marine Debris”, Hatfield Marine Science Center, Auditorium. (OSU and Surfrider Foundation OR region), Mar 21, 2016. https://oregon.surfrider.org/monitoring-marine-debris-with-remote-web-cam-technology/

THEME III – Rafting of species

Cape Perpetua Land/Sea Symposium IV. Yachats, Oregon. 17 November 2016. (3 posters)

Carlton, J.T., Chapman, J., Geller, J., Miller, J.A., Ruiz, G., Carlton, D., McCuller, M. Tsunamigenic Megarafting: The Invasion Process Model and the Long-Distance Transoceanic Dispersal of Coastal Marine Organisms by Japanese Tsunami Marine Debris. Ninth International Conference on Marine Bioinvasions in Sydney, January 2016.

Carlton, J.T., Chapman, J.W., Geller, J.B., Miller, J.A., Ruiz, G.M., Carlton, D.A., McCuller, M.A., Barnard, R., Treneman, N., and Steves, B. Life rafts on the open sea: Successful long-term transoceanic transport of coastal marine organisms by marine debris. PICES, San Diego, 9 November 2016.

Chapman, J.W., Breitenstein, R.A., Carlton, J.T., Miller, J.A., Furota, T., Otani, M., Takeuchi, I., Porquez, J., Burton, A., and Barton, M. 2016.

Crustaceans adrift: Multiyear observations of Asian marine amphipods, isopods, and tanaids arriving in North American shores on open ocean drift objects generated by the 2011 Japanese Tsunami, PICES, San Diego, 9 November.

Geller, J., Campbell, T., Carlton, J.T., Chapman, J., Heller, P., Miller, J., and Ruiz, G. DNA Barcode and Metagenetic Approaches for Monitoring and Surveillance of Marine Invasive Species in North American waters, with Focus on 2011 Japanese Tsunami Marine Debris-Associated Species. Ninth International Conference on Marine Bioinvasions in Sydney, January 2016.

Gillman, R.A., Miller, J.A., Clarke Murray, C., Carlton, J.T., Ruiz, G.M., Otani, M., Nelson, J.C., Wong, J. Japanese Tsunami Marine Debris (JTMD): A closer look at its passengers. State of the Coast - Oregon's Coastal Conference. Gleneden Beach, OR. (Poster)

Gillman, R.A., Miller, J.A., Clarke Murray, C., Carlton, J.T., Ruiz, G., Otani, M., Nelson, J.C., Wong, J. Distributional, environmental, and life history variation of Japanese Tsunami Marine Debris (JTMD) biota. North Pacific Marine Science Organization 2016 Annual Meeting. San Diego, CA, 2016.

Hansen, G. Marine algae of the Japanese Tsunami Floating Dock -- a progress report. Regional Preparedness and Response Workshop to address Bio-fouling and Marine Invasive Species on Japanese Tsunami Marine Debris, Portland, Oregon. July 31-August 1, 2012.

Hansen, G. Some marine algae on Japanese Tsunami Debris. Japanese Memorial Dock Dedication, Hatfield Marine Science Center, Newport, OR, March 10, 2013. (Poster and Specimen Display).

Hansen, G. Marine Algae of Tsunami Debris, also Manning the booth. Hatfield Marine Science Center Open House, Newport, OR, April 13, 2013. (Poster and Specimen display)

Hansen, G. Marine algae on Japanese tsunami debris, the preliminary results of the survey. Oregon State University, Dept. of Botany and Plant Pathology, Corvallis, June 6, 2013.

Hansen, G. Marine algae on Japanese tsunami debris and the risk of invasion. Hatfield Marine Science Center, Newport, OR, June 21,2013

Hansen, G. Marine algae on Japanese tsunami debris and the risk of invasion. Mid-Coast Watersheds Council Meeting, Newport, OR, September 5, 2013.

Hansen, G. Marine Algae on Japanese Tsunami Debris 1: the Risk of Invasion. 27th Northwest Algal Symposium, Camp Casey Conference Ctr, WA. October 18-20, 2013.

Hansen, G. Marine algae on tsunami debris and their invasion threat to the NE Pacific. 1st PICES ADRIFT Project Science Team Meeting. Seattle, WA, 30 July–1 August 2014.

Hansen, G. Marine algae on tsunami debris, update on the species. 2nd PICES ADRIFT Project Science Team Meeting. Honolulu, HA, 15-20 March 2015.

Hansen, G.I., Hanyuda, T., and Kawai, H. Marine Algae on Tsunami Debris, a study in progress. Japan-US Marine Debris Public Workshop. Lincoln City and Newport, OR. February 15 & 16, 2013.

Hansen, G.I., Hanyuda, T., and Kawai, H. Japanese marine algae on tsunami debris reaching western North America. Japanese Phycological Society Meeting, Yamunashi University, Japan, March 27-29, 2013.

Hansen, G., Hanyuda, T., and Kawai, H.. Marine Algae on Japanese Tsunami Debris 2: a Tour of the Algae. 27th Northwest Algal Symposium, Camp Casey Conference Center, WA. October 18-20, 2013.

Hansen, G.I., Hanyuda, T., and **Kawai, H**. Marine Algae arriving on Japanese Tsunami Marine Debris (JTMD) and their invasion threat to the coast of Oregon and Washington, USA. 9th International Conference on Marine Bioinvasions. Sydney, Australia, 19-21 January 2016. (Poster presented by H. Kawai)

Hansen, G.I., Hanyuda, T., and Kawai, H. Marine algae carried across the North Pacific on Japanese Tsunami Marine Debris (JTMD) and their invasion threat to the coasts of Oregon and Washington, USA. Marine Sciences Day, Hatfield Marine Science Center. Newport, Oregon, 11 April 2016. (Poster)

Hansen, G., Hanyuda, T., Kawai, H. Marine algae carried across the North Pacific on Japanese Tsunami Marine Debris (JTMD) and their invasion threat to the coasts of Oregon and Washington, USA. 9th International Conference on Marine Bioinvasions. The Menzies Sydney Hotel, Sydney, 19-21 January, 2016.

Hansen, G.I., Hanyuda, T., and Kawai, H. Marine algae carried across the North Pacific on Japanese Tsunami Marine Debris (JTMD) and their invasion threat to the coasts of Oregon and Washington, USA. PICES 25 -- North Pacific Marine Science Organization -- 2016 Annual Meeting. San Diego, California. 2-13 November 2016. (Poster)

Hansen, G.I., Hanyuda, T., and Kawai, H. Marine algae arriving on Japanese Tsunami Marine Debris (JTMD) and their invasion threat to the shores of Oregon and Washington, USA. Western Society of Naturalists – 100th Anniversary, Monterey, California. 10-13 November 2016. (Poster)

Hansen, G.I., West, J.A., Hanyuda, T., and Zuccarello, G.C. The Pink Crust, a new-to-science species on hard plastic debris. Marine Sciences Day, Hatfield Marine Science Center. Newport, Oregon, 11 April 2016. (Poster)

Hansen, G.I., West, J.A., Hanyuda, T., and Zuccarello, G.C. Tsunamia transpacifica, a new-to-science pink crust on hard plastic debris. PICES 25 -- North Pacific Marine Science Organization -- 2016 Annual Meeting. San Diego, California, 2-13 November 2016. (Poster)

Hansen, G.I., West, J.A., Hanyuda, T., and Zuccarello, G.C. Tsunamia transpacifica, a new-to-science crust on hard plastic debris. Western Society of Naturalists – 100th Anniversary. Monterey, California, 10-13 November 2016. (Poster).

Hanyuda, T., Kawai, H., and Hansen, G.I. Determining the source of the Seal Rock debris boat. Marine Sciences Day, Hatfield Marine Science Center. Newport, Oregon, 11 April 2016. (Poster presented by G.I. Hansen)

Hanyuda, T., Kawai, H., and Hansen, G.I. Determining the source of the Seal Rock debris boat. (A Poster composed by GI Hansen). PICES 25 -- North Pacific Marine Science Organization -- 2016 Annual Meeting. San Diego, California, 2-13 November 2016.

Hanyuda, T., Hansen, G.I., and Kawai, H. Genetic diversity and biogeography of the macroalgal species associated with Japanese tsunami marine debris. PICES 25 -- North Pacific Marine Science Organization -- 2016 Annual Meeting. San Diego, California, 2-13 November 2016. (Talk)

Hanyuda, T., Hansen, G., Kawai, H. Genetic diversity and biogeography of the macroalgal species associated with the Japanese tsunami marine debris. 2016. PICES 2016 Annual Meeting. Omni San Diego Hotel, San Diego, CA, USA, 2-13 November, 2016. (Oral by Kawai, H.)

Hanyuda, T., Kawai, H., and Hansen, G.I. Determining the source of the Seal Rock debris boat. Western Society of Naturalists – 100th Anniversary. Monterey, California, 10-13 November 2016. (Poster).

Invertebrate diversity presentations: There have been numerous presentations at various colleges and universities over the years. Presentations were also made at the VIII International

Conference on Marine Bioinvasions in Vancouver, British Columbia in 2013 and at the IX ICMB in Sydney, Australia in 2016. A summary presentation was made at the PICES Science Meeting in November 2016 in San Diego.

Kawai, H., Hanyuda, T., and Hansen, G.I. Species diversity and the threat of introduced macroalgal species arriving on Northwestern American shores via Japanese Tsunami Marine Debris (JTMD). 11th EMECS – Sea Coasts XXVI Joint Conference. St. Petersburg, Russia, 22-27 August 2016.

Kawai, H., Hanyuda, T., Hansen, G. Species diversity and the threat of introduced macroalgal species arriving on Northwestern American shores via Japanese Tunami Marine Debris (JTMD). 11th EMECS Conference, Azimut Hotel, St. Petersburg, Russia, 22-27 August, 2016. (Poster).

Kawai, H., Hanyuda, T., Hansen, G. The threat of introduced macroalgal species arriving on Northwestern American shores associated with Japanese tsunami marine debris (JTMD). 9th Asia-Pacific Conference on Algal Biotechnology. Century Park Hotel, Bangkok, Thailand, 15-18 November, 2016. (Oral by Kawai, H.).

Miller, J. Invasive Species and Tsunami Debris. Heceta Head Coastal Conference, Florence, Oregon. October 26 & 27, 2012.

Miller, J.A. Tracking marine biota on Japanese tsunami marine debris. Seventh International Symposium on Aquatic Animal Health, Portland, Oregon, 2014

Miller, J.A., Carlton, J.T., Chapman, J., Geller, J., Ruiz, G. The Mussel *Mytilus galloprovincialis* on Japanese Tsunami Marine Debris: A Potential Model Species to Characterize a Novel Transport Vector, Ninth International Conference on Marine Bioinvasions in Sydney, January 2016.

Oregon Department of Fish and Wildlife. Marine Science Poster Review. Newport, Oregon. 15 November 2016. (3 posters)

Ruiz, G., Geller, J., Carlton, J.T., Chapman, J., Miller, J., Di Maria, R., Lohan, K., Barnard, R. Japanese Tsunami Marine Debris: Potential Transoceanic Rafting of Bivalve Parasites and Pathogens, Ninth International Conference on Marine Bioinvasions in Sydney, January 2016.

West, J.A., Hansen, G.I., Hanyuda, T., and Zuccarello, G.C. Flora of Drift Plastics: a new red algal genus, Tsunamia transpacifica (Stylonematophyceae) from Japanese tsunami debris in the northeast Pacific. The Green Planet – Past, Present, and Future. Calcutta, India. 21-23 December 2016..

羽生田岳昭「東日本大震災由来の漂着物に着生した海藻類の種及び遺伝的多様性について」2016 年度藻類談話会 奈良女子大学理学部 2016 年 11 月 19 日

羽生田岳昭・Hansen, G.I.・川井浩史「東日本大震災由来の漂着物に着生していた海藻類の種多様性及び遺伝的多様性」日本藻類学会第40回大会 日本歯科大学2016年３月18-20日

Outreach and Education

Watch for Invasive Wakame on Tsunami Debris! June 15, 2012. A Flyer by GI Hansen on *Undaria pinnatifida* that has been widely distributed, posted on the Coast Watch website, and incorporated into the training program for Oregon Parks and Recreation volunteers.

Collecting Marine Algae from Tsunami Debris for Identification. June 19, 2012. An OPRD educational handout by G. Hansen.

Coping with Marine Debris. July 2012. A library exhibit prepared by S. Gilmont that included my Flyer and my specimens of *Undaria pinnatifida.*

Ideal collections of biota from marine debris. March 16, 2013. A Handout for Oregon State Agencies and Volunteers by.J. Miller, G. Hansen, and J. Chapman.

Some Marine Algae from Japanese Tsunami Debris. April 13, 2013. A general public poster by G. Hansen, updated in 2016 and widely distributed.

川井浩史「海を渡る侵入者～外来種となった海藻類」ドキドキ齊塾遊学会． 大阪市立大学文化交流センター2014年10月3日

Marine Algae of Washington Debris: the Cape Disappointment Tsunami Boat. 2014. An Instructional Power Point Presentation for use in Washington -- provided to Allen Pleus, Aquatic Nuisance Species Coordinator of Washington Dept. of Fish and Game and to J. Carlton for an NSF Biofouling Report.

川井浩史「外来種としての海藻類」奈良女子大学共生科学研究センター国際シンポジウム「外来生物に関する近年の進展」奈良女子大学．2014年11月8日

Japanese Tsunami Marine Debris, Key Aquatic Invasive Species Watch. 2015. Oregon Sea Grant, 12 pp. Authors include: Jennifer Lam and Sam Chan (OSU/Oregon Sea Grant); Gayle Hansen, John Chapman, and Jessica Miller (OSU); Jim Carlton (Williams College); Rick Boatner (ODFW); Rick Cooper, Pat Kight, Tania Siemens, and Kayla Martin (Oregon Sea Grant); Jared Corcoran (designer).

川井浩史「海藻類から見た海の環境：環境指標と外来種」神戸大学理学部サイエンスセミナー神戸大学百年記念館大講堂2015年7月25日

Marine Debris Action Plan Workshop, in Newport, OR. April 13-14, 2016. Reva Gillman attended the Marine Debris Action Plan Workshop, put on by the NOAA Marine Debris Program. While there, she showcased samples of JTMD species, as well as presented an informational poster on JTMD species to participants of the Marine Debris Workshop. She also sent out additional materials (informative JTMD species booklet) later on for those who were interested.

Reva Gillman presented a talk for students from the Educational Opportunities at OSU. September 16, 2016. She gave a tour of the Miller lab and the rest of Hatfield Marine Science Center for soon-to-be OSU undergraduate freshman. The students were from underrepresented groups. They were shown samples of JTMD species and discussed the research. They were also shown the display that included a piece of the Japanese dock that washed up in Newport, OR, (the Agate Beach Dock) as well as the exhibit at Hatfield Marine Science Center showcasing JTMD species.

Chapter 19: Project Science Team and Research Team members

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