North Pacific Marine Science Organization (PICES)
PICES-MoE project on "*Effects of marine debris caused by the Great Tsunami of 2011*"

Years 1-3 Final Scientific Report

Research Project:

Japanese Tsunami Marine Debris (JTMD) and Alien Species Invasions: Characterization of the Biodiversity Arriving with JTMD in North America and the Hawaiian Islands

Submitted by:

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1. PROJECT INFORMATION

Title	*Japanese Tsunami Marine Debris (JTMD) and Alien Species Invasions: Continued Characterization of JTMD Biodiversity*
Award period	*April 1, 2016 - March 31, 2017*
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Lead Author of Report*	*James T. Carlton*

**Although there may be only one lead author of the report, all PIs and co-PIs of the project, as identified in the approved statement of work and listed below, are responsible for the content of the Final Report in terms of completeness and accuracy.*

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2. Year 3 Progress Summary

a. Progress

Our work assessing the range of biodiversity on JTMD objects continued steadily and on target in Year 3. We worked through and completed analysis of more than 100 additional samples, some of which had been archived at OSU and were received by us in June 2016, while continuing to work with colleagues from Washington, Oregon, and Hawaii receiving samples from new landings. At the same time, shipments of voucher specimens for analysis and identification by co-operating taxonomists (see METHODS, below) continued apace, in order to attempt to finalize identifications and permit these systematists to work on their manuscripts for a special issue of *Aquatic Invasions* in 2017 (see PUBLICATIONS, below).

In turn, 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, so that future workers would have access to this unique resource, especially with the undoubted advance of new analytical techniques in years to come.

Work further continued on the JTMD Biodiversity Database, recording the individual species on every object, whether they were alive or dead, and their biogeographic status (Western Pacific origin, acquisition in the transiting oceanic pelagic environment, or Eastern Pacific origin). Our field of taxonomists, as diverse as the species themselves, continued to provide us with a seemingly never-ending stream of taxonomic changes, updates, revisions, amendments, modifications, alterations, corrections, and other adjustments, which permitted us to bathe in the luxury of ever-refining biodiversity resolution.

b. Concerns or Challenges

None of note.

3. ABSTRACT

More than 650 objects related to the Great Tsunami of 2011 arriving 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 in the Central and Eastern Pacific Ocean since the summer of 2012. Remarkably, at least four new species of marine life have been detected on JTMD. Invertebrate diversity was dominated by 6 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 compose over 40% of the diversity; all six groups combined account for nearly two-thirds of the diversity. Cumulative species richness mirrors debris arrivals in spring, 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*, itself a 20th century invasion of Japanese waters. Very common was the Western Pacific bryozoan *Scruparia ambigua*, occurring on one-third of all objects, followed by the large Asian rose barnacle *Megabalanus rosa*. Two thirds of the most common species are bivalves, bryozoans, and 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 3 unique species aboard account for half of these species alone, or approximately 20% of the biota; an additional 45 objects, each with 1 or 2 unique species, account for the remaining presence of "one-off" occurrences. The number (40) of species arriving dead is surprisingly few, given the length and time duration of the voyages across what is usually considered to be a largely hostile environment for coastal species. 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 were acquired by the debris from south of the Tohoku coast, during ocean rafting. These species appear 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 of the Western North Pacific over time. Remarkably, Japanese tsunami marine debris 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.

4. PROJECT DESCRIPTION

a. Research Purpose

The purpose of the biodiversity portion of the ADRIFT project was to attempt to assess the overall breadth and depth of the diversity of the invertebrate and fish fauna associated with the debris field generated by the March 11, 2011 Japanese Earthquake and Tsunami and subsequently rafting, over the ensuing years, to the Hawaiian Islands and to North America.

b. Objectives

Our objectives included obtaining the widest variety of biological samples over time and space as feasible and practicable; processing and sorting these as assiduously and efficiently as possible to the lowest possible taxonomic level, permitting either identification in our laboratory, or by sending specimens to specialized taxonomists; continued identifications in our laboratory and extracting identifications from taxonomists in order to populate a JTMD biodiversity data base, and analyze the data for diversity patterns over time and space, as detailed below. A corollary effort was focused on providing fresh tissue samples, where and when possible, to the Geller Laboratory for potential genetic analyses, and providing bivalve mollusk samples (particularly *Mytilus galloprovincialis*) to the Ruiz Laboratory for parasite analysis.

c. 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 Dr. John Chapman and other 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 photodocumentation. As a result, many 100s 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 (Geller) and the Smithsonian Environmental Research Center (Ruiz)

Sample Registry. Each sampled object was assigned a unique JTMD-BF-# (**Appendix 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.

Species Identification. 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 2).**

Sample Quality Assessment for Biodiversity Analyses. 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 invasion 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 to likely have captured the majority of the diversity of species on those objects. These items are referred to as "***Category 1***" objects (**Appendix 1-A**). 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 photodocumentation, 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 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:

Formal object identification: Registration numbers or other numeric identification present on a object, which data could then be provided to the Japanese Consulate.

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.

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.

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 in line with modeled debris arrival timing. 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.

d. Results

JTMD Objects Analyzed

Total Objects and Geographic Breadth.
To date, 653 objects have been registered and analyzed in whole or in part for the marine life attached to these objects (**Appendix 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.

Object Diversity.
Objects included **vessels**, **totes** (crates, boxes, pallets, boxes), **buoys** (floats), and many **other** objects as one might expect to be derived from towns and industries along the Tohoku coastal zone (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.

More than 70 ***vessels*** were sampled that were derived from the tsunami strike zone (including Aomori, Iwate, Miyagi, and Fukushima Prefectures; as noted above**,** no vessels that could be traced-to-source were from any other region of Japan). 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 were as follows: Alaska (17 detected / 0 sampled), British Columbia

(15/2), Washington (27/24), Oregon (35/30), California (4/2), Hawaii (54/17). Thus, nearly 90% of all vessels that landed and were detected in Washington and Oregon were sampled at some level. Of all vessels sampled, slightly more than 40 satisfied the criteria for "Category 1," as detailed in Methods above.

Post-and-beam wood had a relatively short sea life: first arriving in 2013, in concert with general predictions that objects with no or little windage would require approximately 2 years to transit the North Pacific, the wood appeared to be largely gone by 2014, having thus been at sea for 2 to 3 before extinction. This low survival of wood is 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 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 (**Box 1**). Post-and-beam wood found on beaches after 2014 appear to have either been ashore for more than a year and gone undetected, or were beached by storms somewhere in the North Pacific for some length of time, and then subsequently refloated to resume their journeys to North America or the Hawaiian Islands.

The two ***docks*** from the Port of Misawa have been extensively referenced and discussed in many venues over the past 5 years. Four large docks using 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 1**). "Misawa 1" ("M1," or JTMD-BF-1) landed on the central Oregon coast, USA, on June 5, 2012. "Misawa 2" ("M2") drifted past the Hawaiian Islands in September 2012, but was never seen again. "Misawa 3" ("M3," or JTMD-BF-8), landed on the Washington coast, USA, on December 18, 2012.

Patterns of Object Arrival over Space and Time

Object arrival over time (**Figure 2**) had a relatively consistent pattern of stair-cased spring pulse landings, with a cumulative curve indicating that overall arrivals have not yet plateaued. The number of certain larger object types (vessels, buoys, and totes) arriving has slowly decreased over time, but continue to arrive as of December 2016.

Box 1. New Species of Marine Life Detected During PICES ADRIFT (JTMD) Research

At least four new species of marine animals and plants have been detected on Japanese tsunami marine debris during the course of PICES ADRIFT research.

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.

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*.

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, curiously unknown, but it may be a member of the oceanic neustonic guild of the North Pacific. A ***second new species of red algae, also in the class Stylonematophyceae***, was also detected, but has not been described (West et al., 2016, Algae 31:289-301).

JTMD Biodiversity Assessment

Total Biodiversity 2012-2016

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 3**) and approximately 80 species of algae, or seaweeds (G. Hansen, in a separate report). 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 debris origin itself.

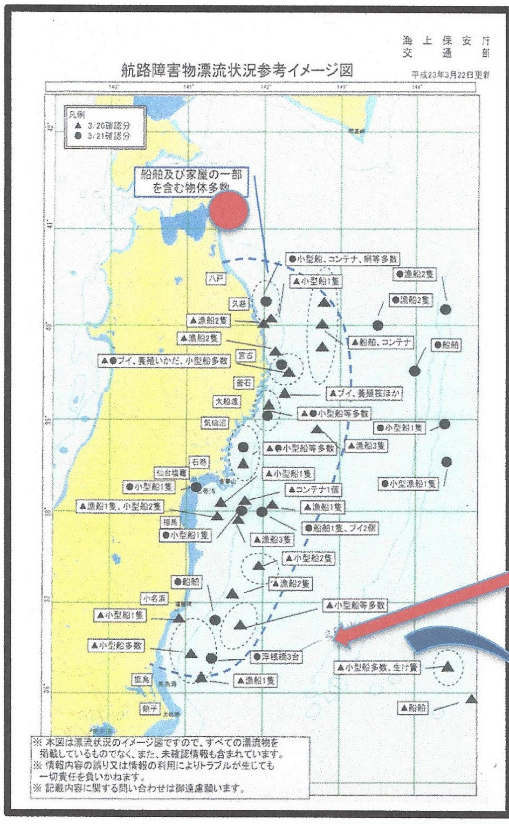
The fishing dock **Misawa 1** arrived with more than **130** living species aboard, including microbiota, macroinvertebrates, and algae (seaweed). Six months later, **Misawa 3** arrived with half that total diversity (**66** species). Aboard Misawa 1 were *84 macro-invertebrate species*; Misawa 3 arrived with *15 additional species* not found on Misawa 1. Thus, Misawa 1 + Misawa 3 arrived with approximately100 species, or nearly one-third of the total biota that was to arrive 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 nearly 25 species that were unique to these first two large arrivals in 2012.The acquisition of a faint southern biological signature by both docks is discussed below.

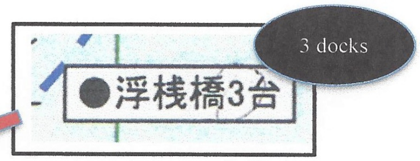
Remarkably, at least four new species of marine life have been detected on Japanese tsunami marine debris **(Box 1**), which have been or are in the process of being described.

Macro-Invertebrate Biodiversity

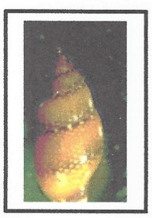
Invertebrate diversity was dominated by 6 groups **(Table 1, Figures 3a** (richness) and **3b** (percentage relative composition)): **bryozoans** (moss animals), **bivalves** (mussels, scallops, oysters, clams, and shipworms), **polychaetes** (marine worms), **hydroids**, **gastropods** (shelled snails and nudibranchs) and **sponges**. The first three groups comprise over 40% of the diversity; all six groups combined account for nearly two-thirds of the observed diversity (**Table 1**). In **Figures 3a** and **3b**, **Annelida** are primarily polychaetes, with the inclusion of rare oligochaetes and **Cnidaria** include 7 species of sea anemones and corals. **Crustacea**, in aggregate, rank in the higher diversity bins when barnacles, amphipods, isopods, tanaids, and decapods are combined.

Figure 1. **Acquisition of southern signature species by *Misawa 1* (JTMD-BF-1) and *Misawa 3* (JTMD-BF-8) before departure to North America.**



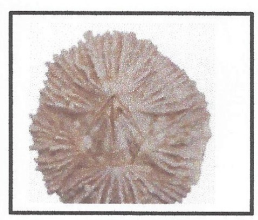


On March 21, 2011, 3 of the 4 Misawa docks were reported by the Japanese Coast Guard about 80 km northeast of Tokyo



Snail
Mitrella moleculina

Ark shell
Arca navicularis



Barnacle
Pseudoctomeris sulcata

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.

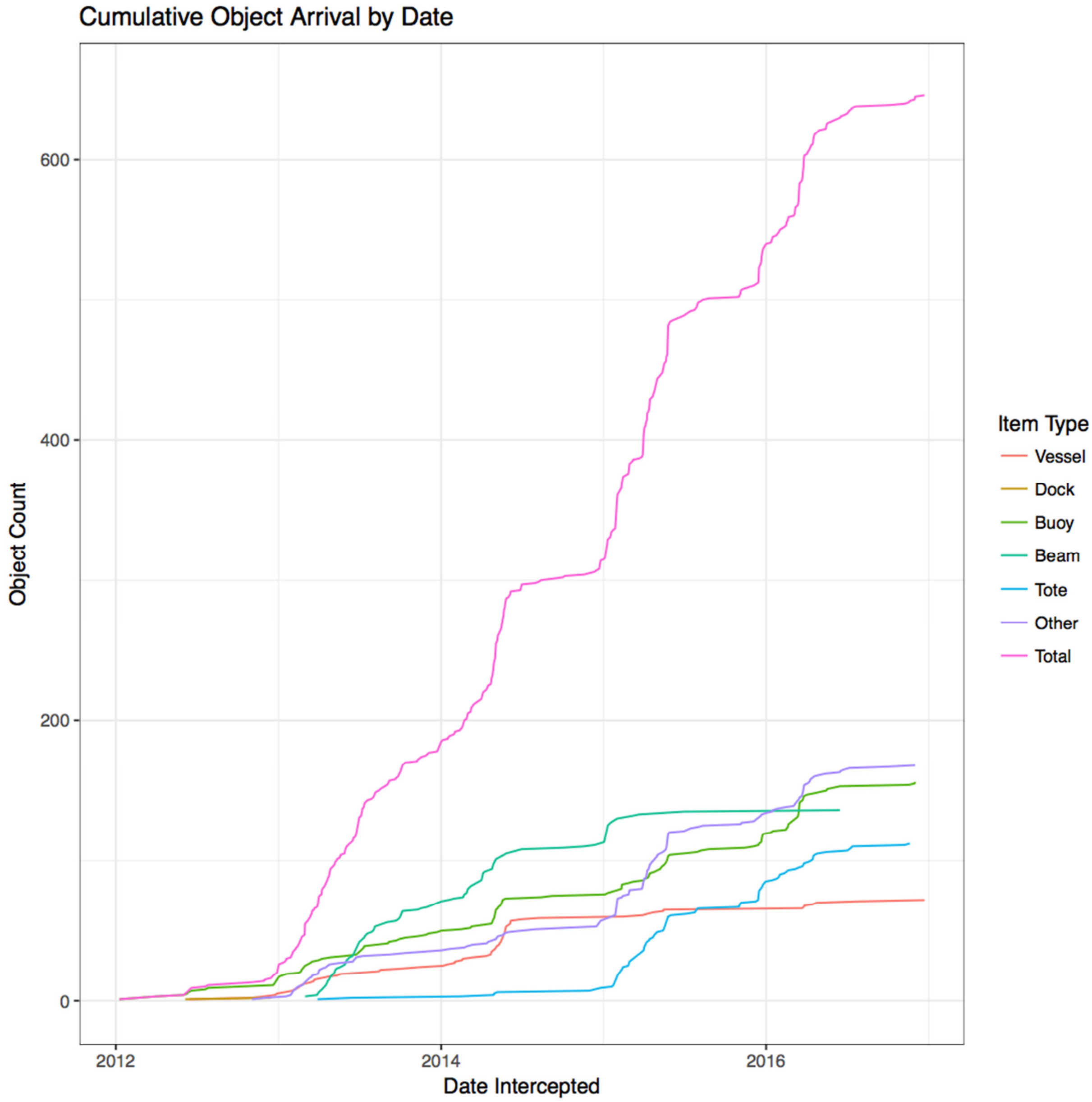


Figure 2. Cumulative JTMD object arrival over time.

Table 1. Overview: JTMD Biodiversity

	Group					
A	Rhizaria (including foraminifera)	14				
B	Ciliophora	6				
C	Invertebrates	**296**	Invertebrates			
			Group	**(n spp.)**	% (of **E**)	% (of **F**)
			Bryozoa	49		
			Bivalvia	46		
			Polychaeta	45		
	Subtotal			**140**	**44%**	**47%**
			Hydrozoa	26		
			Gastropoda	20		
			Porifera	18		
	Subtotal			**204**	**64%**	**68.5%**
D	**Fish**	2				
E	**Subtotal All Taxa A, B, C, D (Rhizaria, Ciliophora, Invertebrates, Fish)**	**318**				
F	**Subtotal C + D (Invertebrates + Fish)**	**298**				
G	For macroscopic diversity pattern analyses, less invertebrate microbiota (nematodes, platyhelminthes, copepods, ostracods, acarina)	*(- 31)*				
H	**Total for Macro-Invertebrate Spatial and Temporal Diversity Analyses**	**267**				

Cumulative Species Richness and Declining Richness Over Time

Cumulative species richness mirrors debris arrivals in *spring, staircase-like pulses* (**Figure 4**). Overall cumulative diversity has not yet reached an asymptote, suggesting that total arriving diversity of macroinvertebrates was likely considerably larger (rarefaction analyses are in progress). That said, analysis of species richness focused on "Category 1" vessels (**Figure 5**), demonstrates declining diversity since 2014, as might be expected from longer and longer sea voyages by coastal species.

Most Frequent Arrivals

Twelve invertebrate species occurred on 35 or more objects (**Table 2**). More than 40% of all objects transported the large marine Mediterranean mussel *Mytilus galloprovincialis*, itself a 20th century invasion of Japanese waters. Very common, too, was the Western Pacific encrusting marine bryozoan *Scruparia ambigua*, occurring on one-third of all objects, followed by the large Asian rose barnacle *Megabalanus rosa*. Two thirds of the most common species are bivalves, bryozoans, and barnacles

Table 2. The 12 most frequent marine invertebrates found on Japanese Tsunami Marine Debris (2012-2016), based on those species occurring on more than 35 objects.

Taxon	**Species**		**# 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 3. Unique species occurrences in 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 **4** (45 additional items with 1 or 2 unique species)		53		various	see A-**4**	2012-2016
Total		**109**	**40.8 %**			

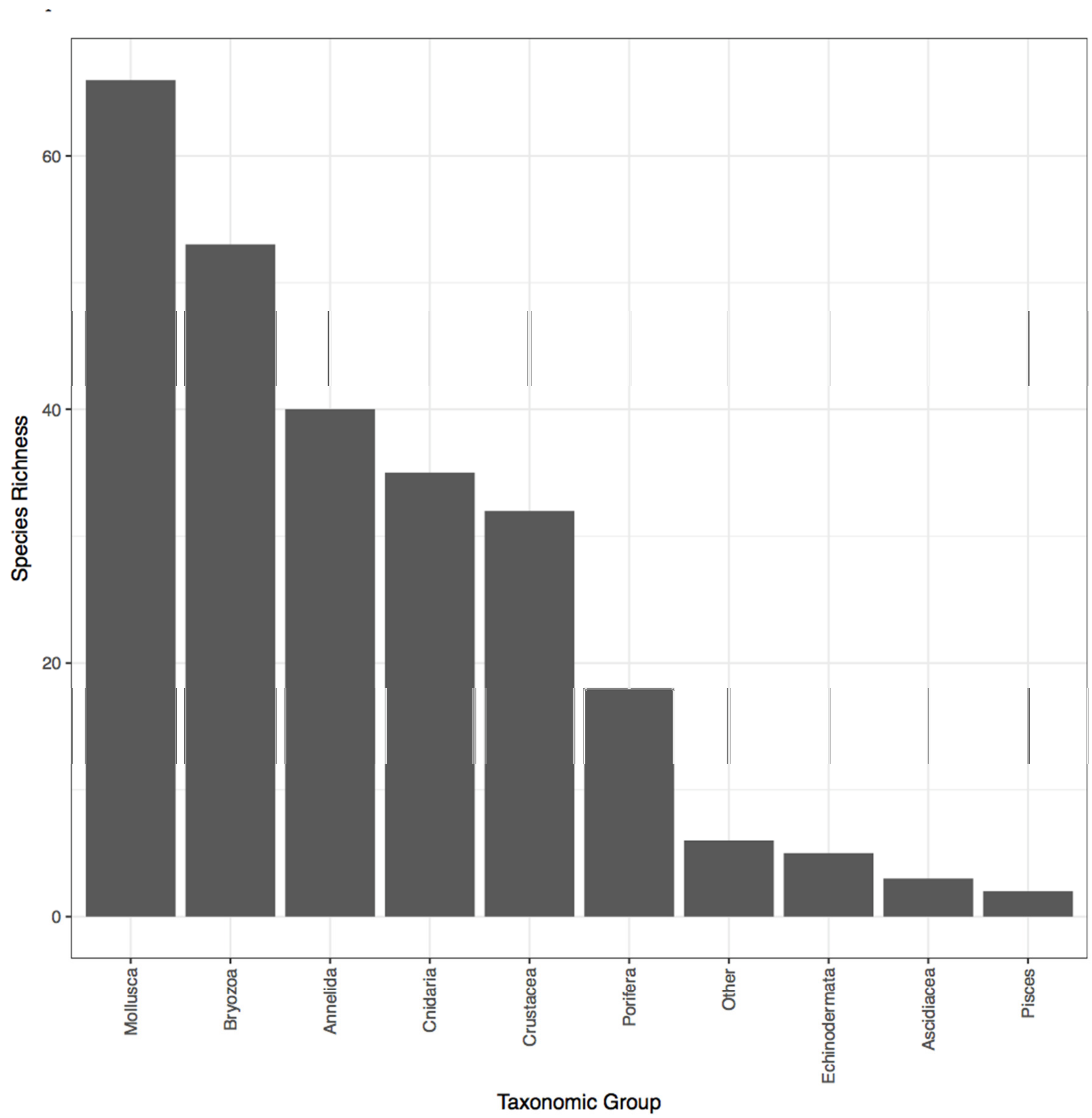


Figure 3a. Richness of JTMD biodiversity by taxonomic group.

(**Table 2**). All common species arrived alive in North American waters, with at least 7 species surviving the warmer, oligotrophic voyage to the Hawaiian Islands.

Biodiversity for Temporal and Spatial Pattern Calculations

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; rows A and B, **Table 2**) and the microbiota guilds (of about 30 species; row G, **Table 2**) are not considered, as their sampling was uneven across objects and regions during the course of the work. Thus, the effective denominators for analyzing overall diversity are 298 species (row F, **Table 2**) and 267 species (row H, **Table 2**).

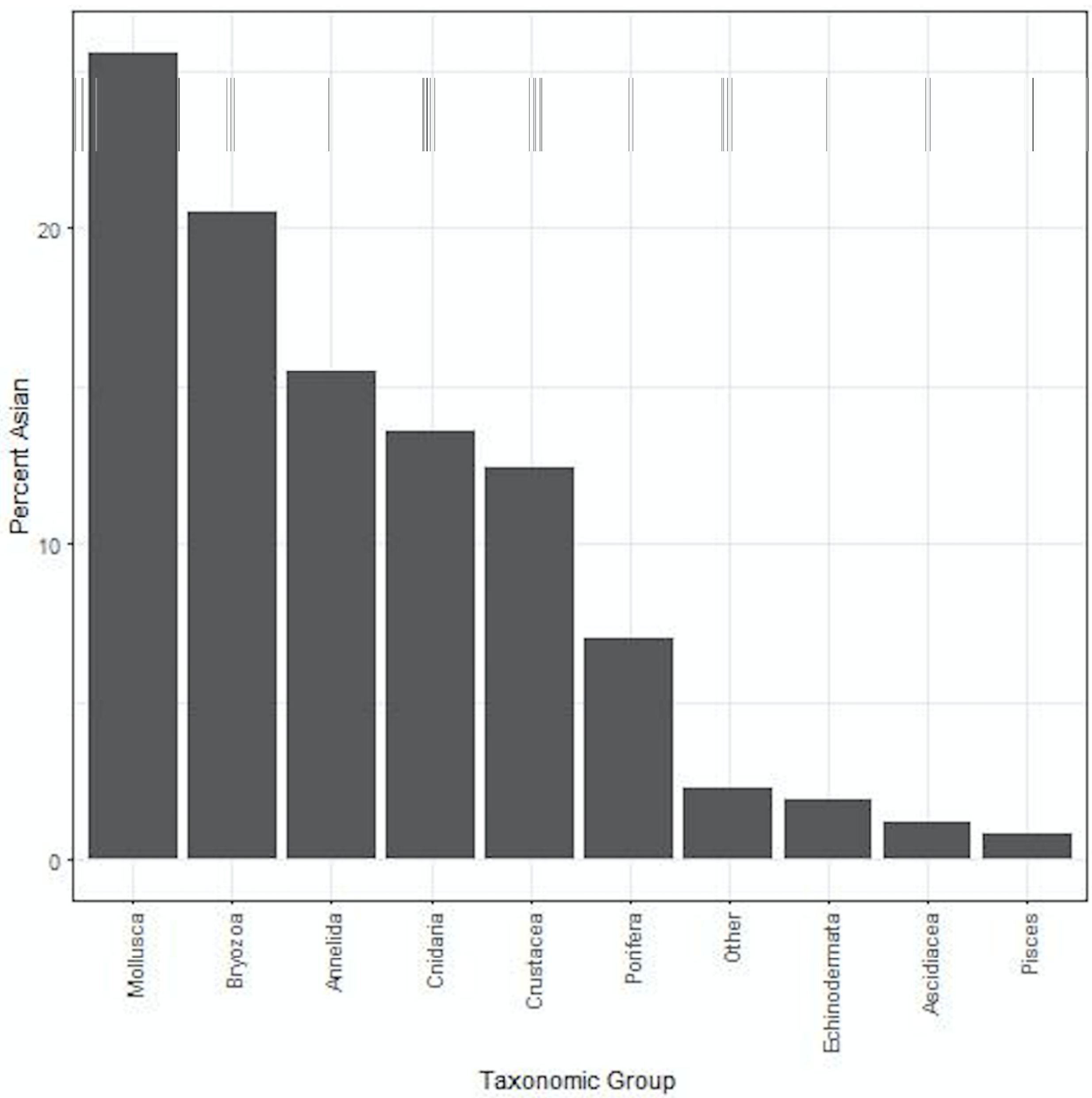


Figure 3b. Percent composition of JTMD diversity by taxonomic group.

Unique Species

No fewer than 109 species -- or 40% of the total macro-invertebrate and fish diversity -- were found only once (**Table 3**). Eight objects with more than 3 unique species aboard account for half of these species alone (**Table 3**), or approximately 20% of the biota; an additional 45 objects, each with 1 or 2 unique species, account for the remaining presence of "one-off" occurrences (**Appendix 4**).

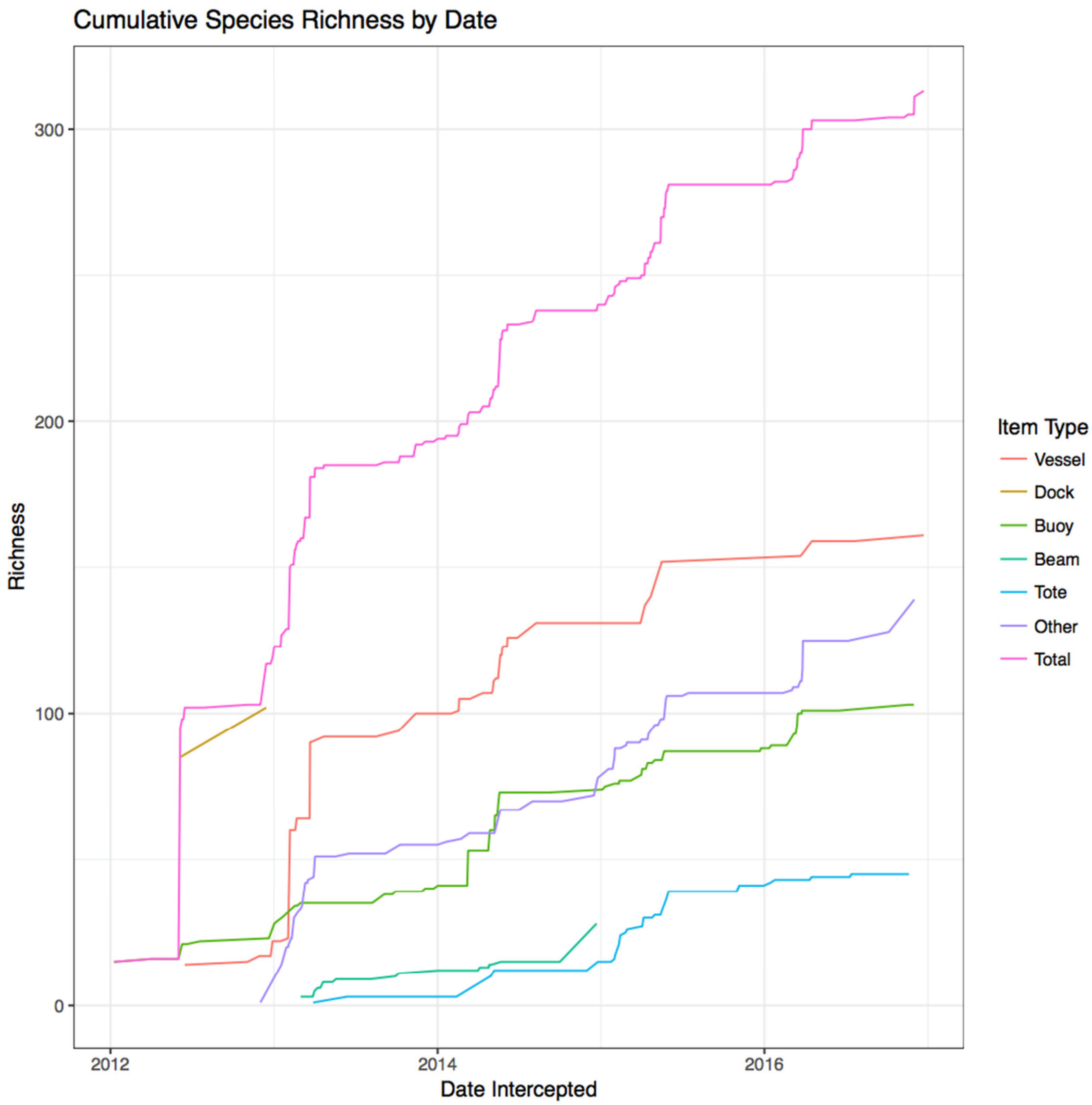


Figure 4. JTMD cumulative species richness over time.

Species Attrition

As expected, not all species survived the voyage (**Appendix 5**). This said, the number arriving as dead-only taxa is surprisingly few, 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. Of the bivalves, 8 to 10 species have subtropical-tropical affinities. Six of these species (**Appendix 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. All together, a little less than one-third of the species arriving dead are warm-affinity taxa (see section below and **Appendix 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 arrived alive at other times and locations on

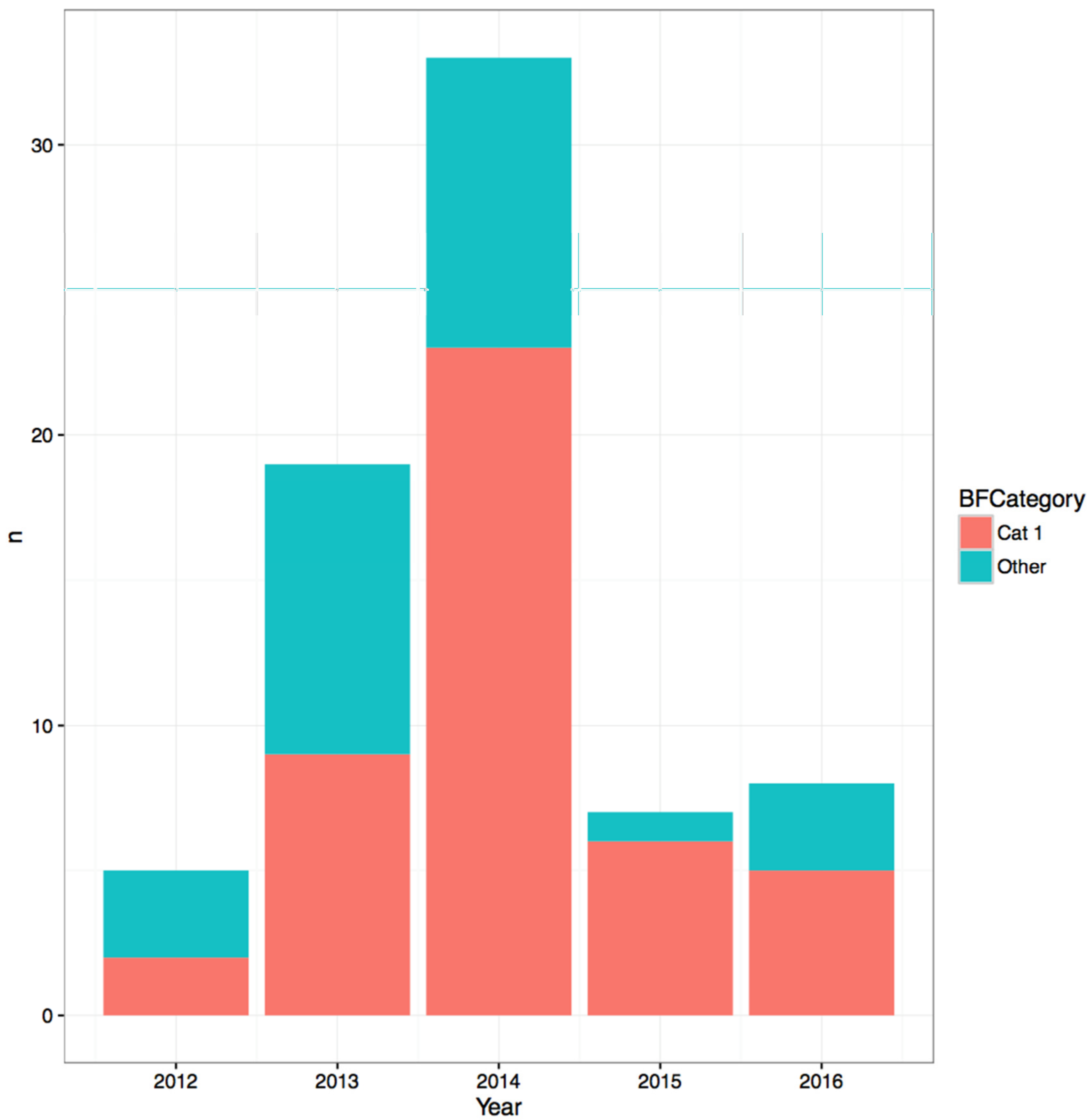


Figure 5. Richness decreasing on "Category 1" vessels over time.

objects not accessed and sampled. Thus, for example, tropical oysters, scallops, chamids, arriving in the Pacific Northwest may have also arrived on undetected / unsampled debris in the Hawaiian Islands. Further complicating our full assessment of mortality patterns is that it is not always possible to determine whether a given species died after arrival on a particular shore, but before sampling was possible; thus, post-landing mortality may have artificially inflated the number of species appearing not to survive the voyages.

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, is that the overall ratio of living vs. dead arrivals should shift 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

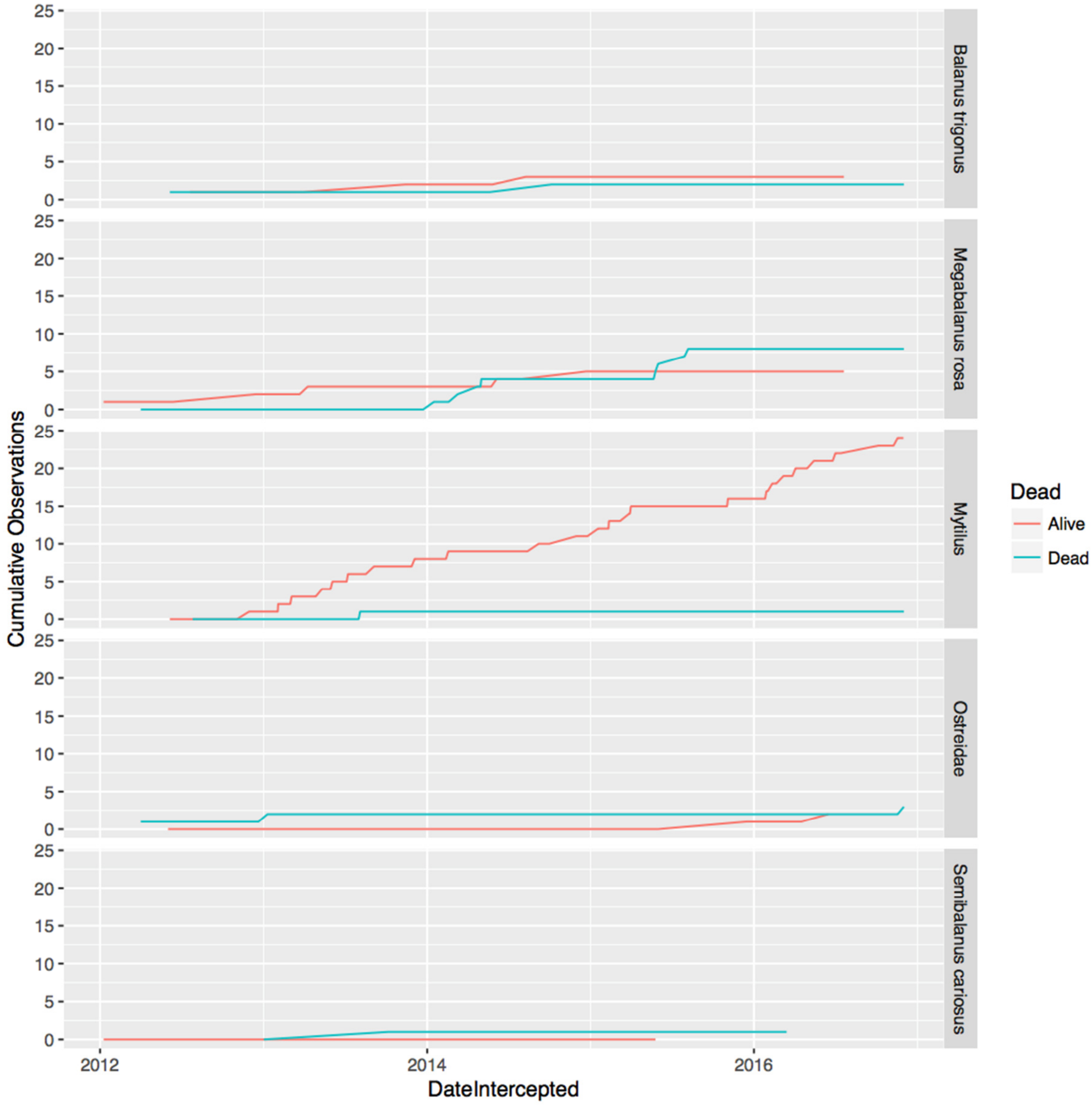


Figure 6. JTMD species survival over time.

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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 6**). A detailed example of the jump in mortality for the rose barnacle *Megabalanus* is shown in **Figure 7**, with more dead than alive arriving by late 2015. A singular exception is the remarkable survival of the mussel *Mytilus galloprovincialis*, with the number of living individuals always exceeding the number of dead mussels over time (**Figure 8**). Little is understood of the oceanic physiology of this bivalve to understand its ability to sustain for multiple years on the high seas.

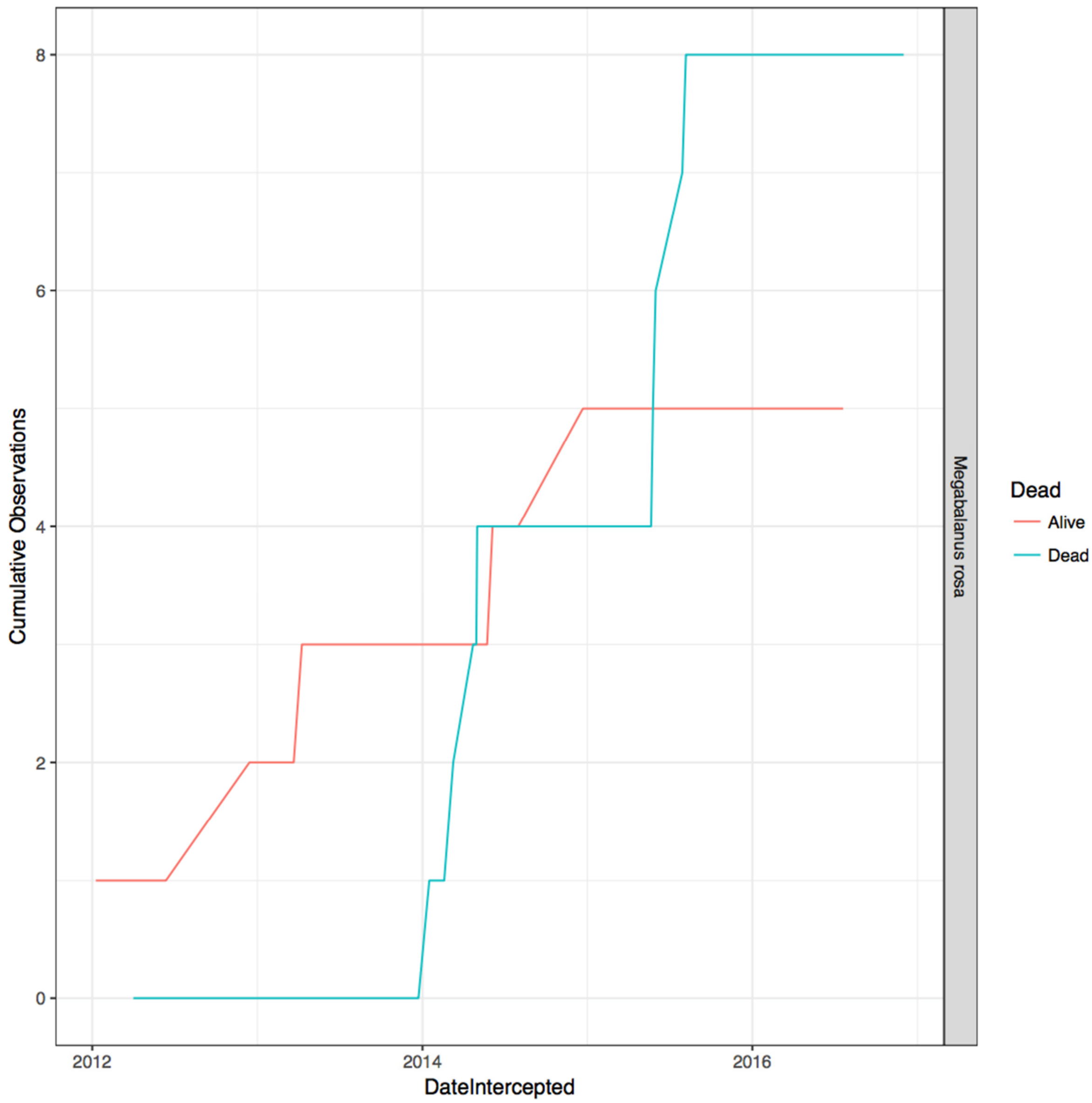


Figure 7. The barnacle *Megabalanus rosa* survival over time.

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 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.

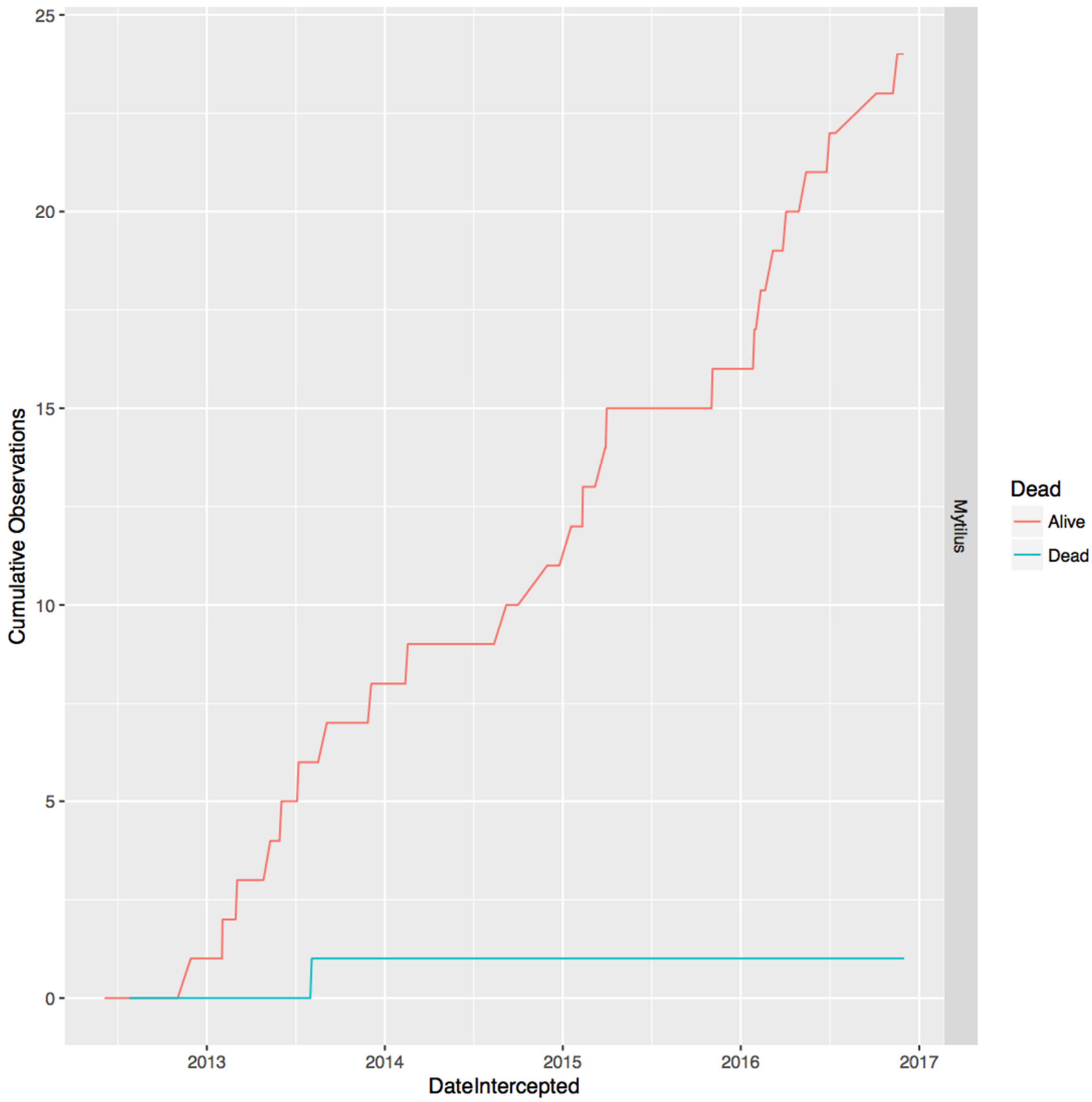


Figure 8. The survival of JTMD mussels, *Mytilus galloprovincialis*, over time.

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 (房総半島). A number of species only occur as far north as the Kii Peninsula (紀伊半島), while others occur north to Amami Islands (奄美群島), or even only to the South China Sea. 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 discussion in box on **Figure 1**). Critically, 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 of the Western North Pacific; as noted above, 12 of the 37 southern taxa arrived dead (but may have arrived alive, as also discussed earlier, on non-sampled debris).

The Spring 2016 Sea Anemone Pulse. A remarkable JTMD landing event occurred in a 47-day episode between March 3 and April 18, 2016. A "wave" of sea anemones (Cnidaria: Anthozoa: Actinaria), originating from the warm waters of the Western Pacific Ocean, arrived in North America, including two species that had not been detected in the previous 4 years, and 1 species not seen since 2014 (**Figure 9**). 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 arriving 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 9**). Preventing further fine-grained analysis of this curious pattern are observation gaps that characterized much of our understanding of the extent and diversity of JTMD biodiversity landings in North America: in the present case, in terms of marine debris landings, there is a largely unexplored coast from central California to southern Oregon, and, similarly, the coast north of southern Washington is largely unexplored 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, on the 4 arrivals in **Figure 9,** 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 in early March. 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 9** to **Appendix 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.

Figure 9. A 47-day Spring 2016 JTMD Debris and Sea Anemone Landing Event in North America

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

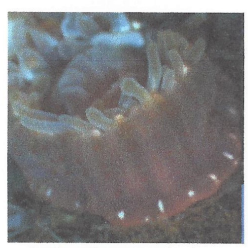
Southern signature or trajectory:

(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 9. JTMD Spring 2016 sea anemone wave on the Pacific coast.

JTMD Continues to Arrive at the end of 2016

Remarkably, Japanese tsunami marine debris 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 4**). While plastic debris may last in the oceans for decades, it remains unclear, as discussed above, what the long-term trajectory is relative to the open ocean survival of coastal species. Species 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 of several decades experience report nothing similar having landed in more than 25 years of observations.

Table 4. Still Living After All These Years: Examples of Marine Life Arriving Alive on JTMD in November and December 2016

JTMD-BF-	Object	Location	Date	Living Japanese species aboard
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	5.5m vessel from Miyagi Prefecture (MG3-38403)	HI: Oahu: Waimanalo	2016 22 December	*Actinaria species B* *Trachypleustes sp.* *Ampithoe sp.*

e. Discussion

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), is 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. This noted, 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 Japanese Tsunami Marine Debris, differ from other anthropogenic vectors that did, do, and will continue to transport species from Japan to North America and Hawaii?

We briefly address both questions here, noting that full treatments of both would form research projects in and of their own.

How does the modern rafting of marine debris with living organisms differ from eons of "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 differ fundamentally in their at-sea longevity from historic rafting. 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 Japanese Tsunami Marine Debris, differ from other anthropogenic vectors that did, do, and will continue to transport species from Japan to North America and Hawaii?

We continue to develop historical, scientific, and policy perspectives on this question, which will be addressed in detail in future publications. 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 a matter of 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.

f. Challenges

None of note.

g. Achievements

This project contributed fundamentally to the overall ADRIFT objectives of assessing the effects of marine debris caused by the Great Tsunami of 2011. A dedicated group of indefatigable scientists, government employees, and citizens over a 5 year period intercepted 100s of debris items along the Pacific coast of North America and in Hawaii which permitted the discovery of 100s of living Japanese species that had successfully rafted to the Central and Eastern Pacific Ocean.

Acknowledgments

Many scores of workers, in aggregate, from Alaska to California and Hawaii, have contributed to the detection, acquisition, and collection of JTMD objects and their associated biota. The many individual collectors will be acknowledged in the publications noted below. Noteworthy in **Washington** have been Russ Lewis (Long Beach) and Allen Pleus, Jessie Schultz, Dustin Courts, and Marcus Reaves of the Washington Department of Fish and Wildlife; in **Oregon**, Nancy Treneman, Dave and Diane Bilderback, and Fawn Custer, among many others; in **British Columbia**, Karla Robison, and in **Alaska**, Tammy Davis. Especially helpful in the **Hawaiian Islands** have been Scott Godwin, Sonia Gorgula, Brian Neilson, Kirsten Moy, Barbara Lee, Megan Lamson and colleagues, and Carl Berg. Providing critical support and assistance on the **Oregon** front have been Jessica Miller, Gayle Hansen, Thomas Murphy and Ralph and Donelle Breitenstein. At all hours of the day and night, Miho Sakuma (Tokyo, Japan) provided assistance with Japanese translations. Critically advancing data handling and data entry was Rebecca Barnard. We further thank, with great debt, the many taxonomists noted in an Appendix, without whom we would have been able to identify only a small fraction of the JTMD biota.

OUTPUTS

a. Completed and planned publications

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

Introduction to Special Issue: Biological and ecological studies of Japanese Tsunami Marine Debris	James T. Carlton, John W. Chapman, Jonathan Geller, Jessica A. Miller, Gregory M. Ruiz, Deborah A. Carlton, Megan I. McCuller, Nancy Treneman, Russell Lewis, David Bilderback, Leslie Harris
Tsunami-generated rafting of **Foraminifera** across the North Pacific Ocean	Kenneth Finger
Porifera collected from Japanese Tsunami Marine Debris on the Northwest coast of North America	David Elvin, James T. Carlton
Hydrozoa	Henry Choong, Dale Calder, James T. Carlton
Polyplacophora (Chitons)	Douglas Eernisse, Anthony Draeger, Erik Pilgrim
Patellidae (Limpets)	Douglas Eernisse, Erik Pilgrim
A Case History of Transoceanic Dispersal: **The Korean Mussel (*Mytilus coruscus*) (Bivalvia: Mytilidae)**	Thomas Therriault, Vanessa Hodes, Geoff Lowe, Tammy Norgard, Cathryn Abbott, Jennifer Yakimishyn, Jonathan Geller, James T. Carlton
Diversity and abundance of **shipworms** (Bivalvia: Teredinidae) in woody debris generated by the 2011 Japanese Earthquake and Tsunami	Nancy C. Treneman, James T. Carlton, Luisa M.S. Borges, J. Reuben Shipway, Michael J. Raupach, Bjorn Altermark
A molecular **phylogeny of shipworms** (Bivalvia: Teredinidae) from Japanese Tsunami Marine Debris	Nancy C. Treneman, Luisa M.S. Borges, J. Reuben Shipway, Michael J. Raupach, Bjorn Altermark, James T. Carlton

Transoceanic transportation of living marine **Ostracoda** (Crustacea) by the tsunami of the 2011 Tohoku Earthquake	Hayato Tanaka, Moriaki Yasuhara, James T. Carlton
Transoceanic Dispersal of Coastal **Barnacles** (Crustacea: Cirripedia) on Japanese Tsunami Marine Debris	James T. Carlton, John W. Chapman, Ralph Breitenstein, Michio Otani
Harpacticoid **copepods** associated with Japanese tsunami debris along the Pacific coast of North America and Hawaii	Jeffery R. Cordell
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)	Megan McCuller and James T. Carlton
Japanese marine **amphipod, isopod, and tanaid crustaceans** arriving in North America on terrestrial and marine debris generated by the 2011 Japanese Tsunami	James T. Carlton, John W. Chapman, Jonathan A. Geller, Jessica Miller, Gregory A. Ruiz, Deborah A. Carlton, Megan I. McCuller, Brian Steves
The Western Pacific **barred knifejaw,** *Oplegnathus fasciatus* (Temminck & Schlegel, 1844) (Pisces: Oplegnathidae) on the Pacific coast of North America	Nicholas Ta, Jessica A Miller, John W. Chapman, Thomas Calvanese, Timothy Miller-Morgan, Kevin Clifford, Evonne Mochon-Collura, James T. Carlton
Trans-Pacific Rafting on Tsunami Associated Debris by the Japanese **Yellowtail Jack,** *Seriola aureovittata* (Pisces: Carangidae)	Matthew Craig, Jim Burke, Kevin Clifford, Evonne Mochon-Collura, John Chapman, and John R. Hyde

Additional papers in preparation include but are not limited to:

Tsunamigenic Megarafting: Implications for Marine Biogeography and Transoceanic Species Dispersal James T. Carlton, John W. Chapman, Jonathan A. Geller, Jessica Miller, Gregory A. Ruiz, Deborah A. Carlton, Megan I. McCuller, Brian Steves. [Overview paper]

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

Description of a new species of Western North Pacific shipworm in the genus Psiloteredo. Nancy C. Treneman, James T. Carlton, Luisa M.S. Borges, J. Reuben Shipway, Michael J. Raupach, Bjorn Altermark

b. Poster and oral presentations at scientific conferences or seminars

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.

c. Education and outreach

No specific education and outreach activities were undertaken.

RESEARCH STATUS AND FUTURE STEPS/PLANS

The project accomplished our purposes, goals, and objectives, by documenting in detail the diversity of the vast array of Japanese marine animals drifting across the North Pacific Ocean and arriving in Hawaii and North America. Our next steps include pursuing systematic work with colleagues on additional JTMD taxa, and to continue to monitor the JTMD field, as time and resources permit, past the current project period. In concert with patterns of the past 4 years, it would not be unusual for a Spring 2017 pulse of debris, with living Japanese species, to arrive on Pacific Northwest shores.