The mussel *Mytilus galloprovincialis* on Japanese tsunami marine debris: A potential model species to characterize a novel transport vector

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Introduction

An unexpected outcome of the tragic 2011 Great East Japan Earthquake and ensuing tsunami was that many living Japanese coastal species were transported more than 5000 km on debris items that made landfall in the Hawaiian Archipelago and in North America. The unexpected arrival of a large concrete dock from Misawa, Japan, on a beach just north of Newport, Oregon in June 2012 demonstrated that certain tsunami debris items could serve as oceanic transport vectors for Japanese coastal species.

Therefore, grants from Oregon Sea Grant and the National Science Foundation supported our initial efforts to track Japanese Tsunami Marine Debris (JTMD) and characterize the biodiversity arriving along the Pacific coast of the United States and Canada and in Hawaii, and we continued this effort as part of the PICES ADRIFT (Assessing Debris-Related Impact from the Tsunami) project with generous funding from the Ministry of Environment of Japan (Clarke Murray *et al*., 2015). We focused on characterizing the biota associated with JTMD; the objects that we considered as JTMD had clear identification such as a serial or registration number that was linked to an object lost during the Great Tsunami of 2011 or had clear biological evidence of originating primarily from the Tohoku coast of Japan. The majority of JTMD biota arrived as adults whereas other vectors, such as ballast water, known to successfully transport non-native species, 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 blue mussel *Mytilus galloprovincialis* (hereafter, *Mytilus*) is a non-native species from the Mediterranean that is established in Japan (and on the Pacific coast of North America) and is common on JTMD, being present on more than 60% of the items that we classified as JTMD. As this species is a predominantly intertidal and shallow subtidal 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. We used this coastal filter-feeding species as a model to explore size, reproduction, growth, and dispersal patterns of JTMD biota. We determined the reproductive status and size frequency distributions of *Mytilus* arriving on JTMD items (docks, pallets, totes, and skiffs) collected from 2012 to 2014. We further resolved aspects of the growth and dispersal history of *Mytilus* on 11 of those JTMD items by completing chemical and structural analysis on the shells of representative mussels. 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.

Size and reproduction of* Mytilus *on JTMD

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 (Fig. 1). This observation, in conjunction with the occurrence of JTMD items from northern Japan arriving with species found only in more southerly locations and the collection of terrestrial origin debris colonized with *Mytilus* and other Japanese biota, indicated that at least some biota settled on these items after the tsunami. From 2012 to 2013, the mean size of *Mytilus* increased by 10 to 19 mm/year on items arriving in Oregon and Washington but not in Hawaii (Fig. 2), suggesting that at least some portion of the biofouling community on JTMD items traveling in more northerly waters continue to grow 2+ years after the tsunami. However, in 2014 there was no observed increase in size of *Mytilus* collected in Oregon and Washington. Furthermore, mussels with mature or maturing gametes arrived through 2014. For 35 JTMD items collected from 2012 to 2014, reproductive individuals were observed in Hawaii (<17% of all mussels examined) and Oregon and Washington (>60%) (Fig. 3), which indicates that they may have released gametes in coastal waters.

Growth and dispersal history of* Mytilus *on JTMD

For chemical and structural analysis, we prepared thin sections of the *Mytilus* shells and focused on the umbo region (Fig. 4), 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. We observed the hypothesized pattern of elevated Ba/Ca during presumed residence in coastal waters (Fig. 5). 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 >2× 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 shell Ba/Ca is 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 NW Pacific coastal waters off Japan – all of which could contribute to increased shell Ba in bivalves.

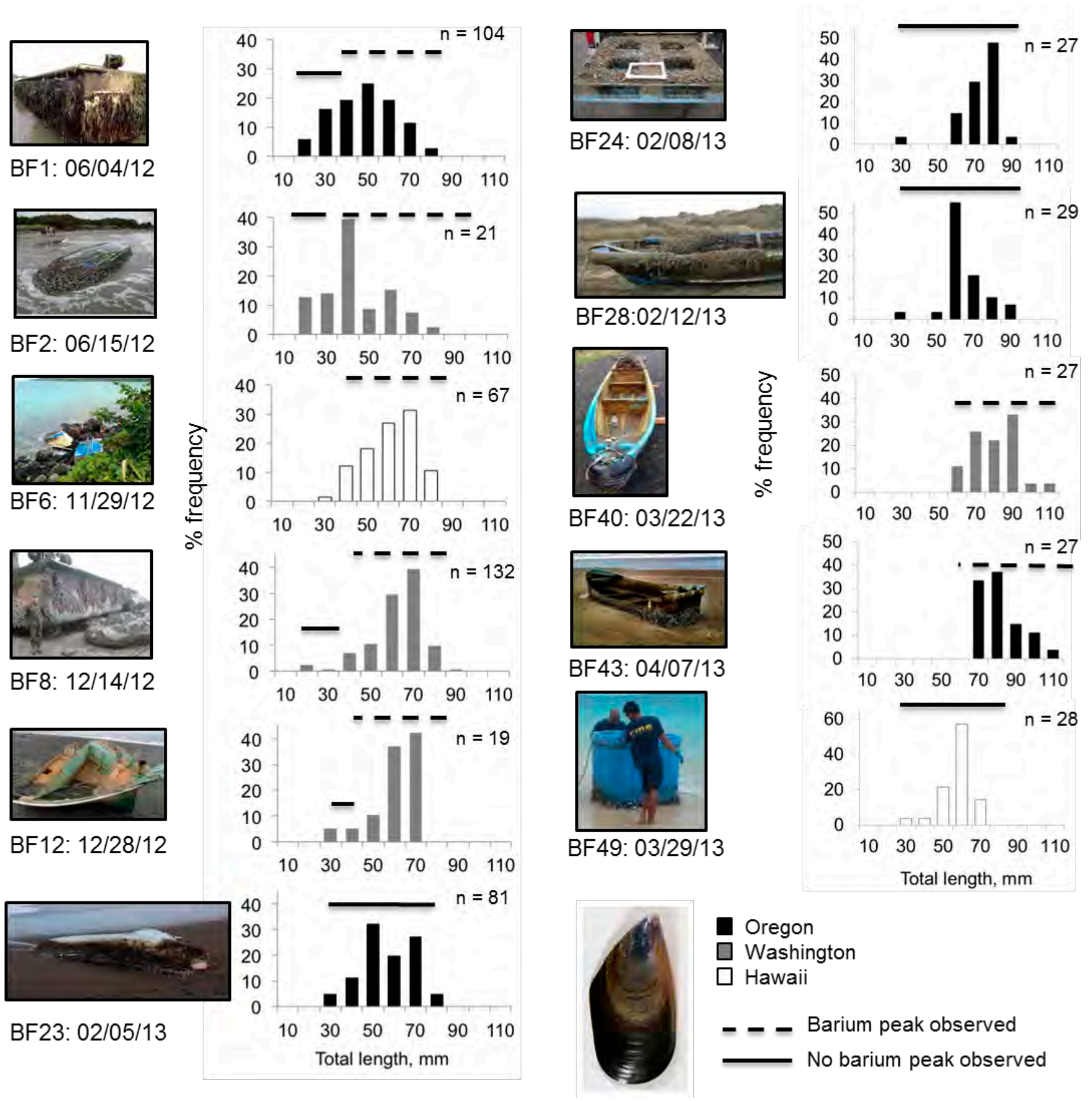

Fig. 1 Size frequency distribution for total shell length (mm) of Mytilus galloprovincialis *on Japanese Tsunami Marine Debris (JTMD) items. Each sampled item was given a unique identification (Biofouling 1 [BF1]). The estimated date of item arrival on local beaches is included along with mussel sample size for each item. The lines above each histogram indicated the size range across which a prominent peak in shell Ba/Ca was observed (dashed line) or not (solid line).*

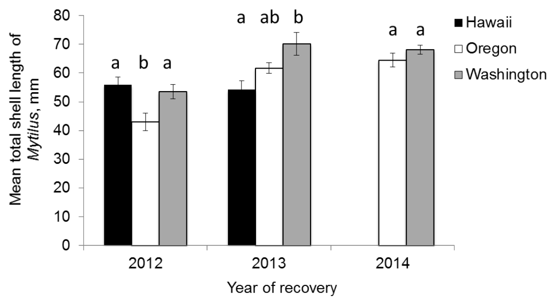

Fig. 2 Mean length (±2 SE) of Mytilus *recovered on JTMD. Letters indicate groups that are statistically similar within years. Across years,* Mytilus *from Hawaii were equivalent in size in 2012 and 2013 whereas Oregon and Washington samples increased in size in 2013, compared with 2012, but then stabilized.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

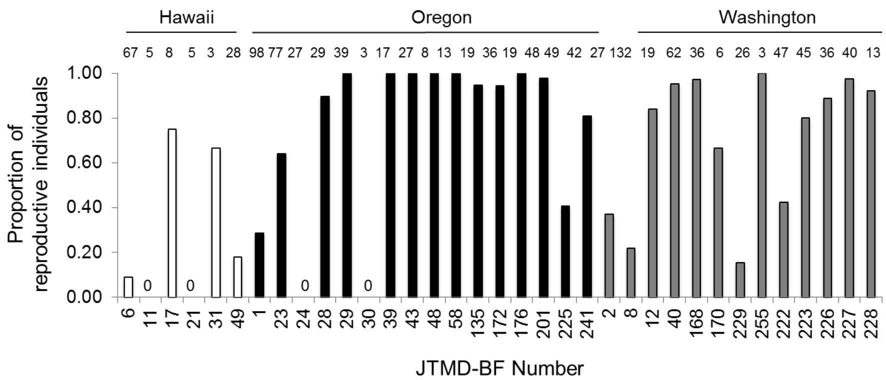

Fig. 3 Proportion of Mytilus *with mature or maturing gametes on various JTMD BF items recovered in Hawaii, Oregon, and Washington. Sample sizes are included at top of graph. JTMD-BF number is along the x-axis and is arranged chronologically within each region with the earliest recoveries (2012) on the left. Mean proportion of reproductive individuals was lowest in Hawaii (0.164, P < 0.01), intermediate in Washington (0.608), and greatest in Oregon (0.693). The difference between Washington and Oregon was marginally significant (P = 0.05).*

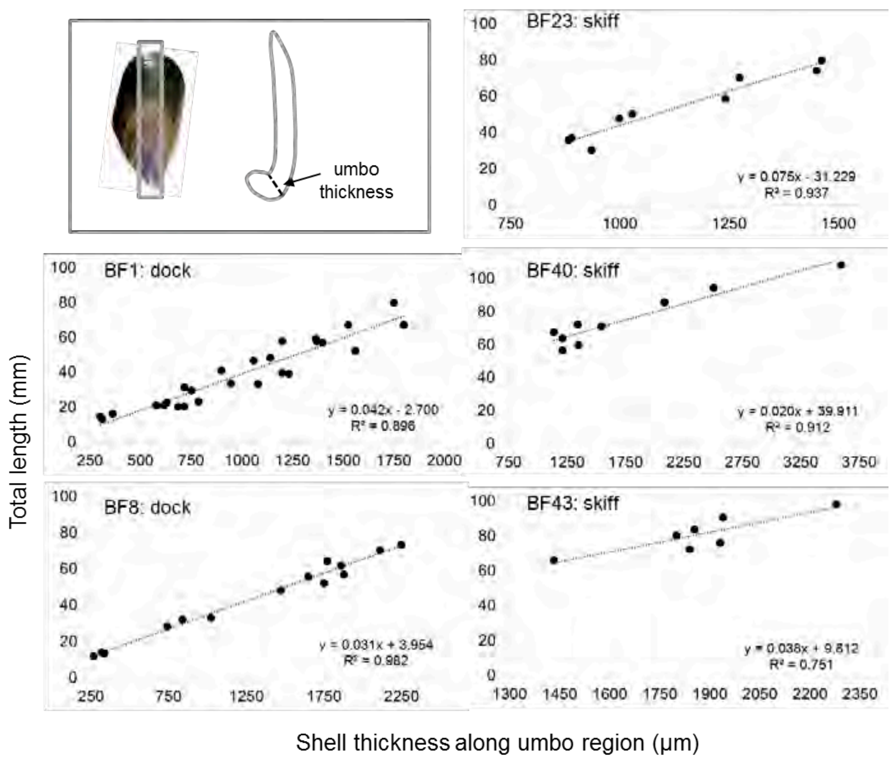

Fig. 4 Back-calculation models for Mytilus *on JTMD BF items collected in 2012 and 2013 showing the relationship between shell length and umbo thickness for five JTMD items. An example of a cross-section that was polished, measured, and ablated (umbo thickness) is shown in the upper left panel. Note that the scale of the shell thickness axis varies among graphs.*

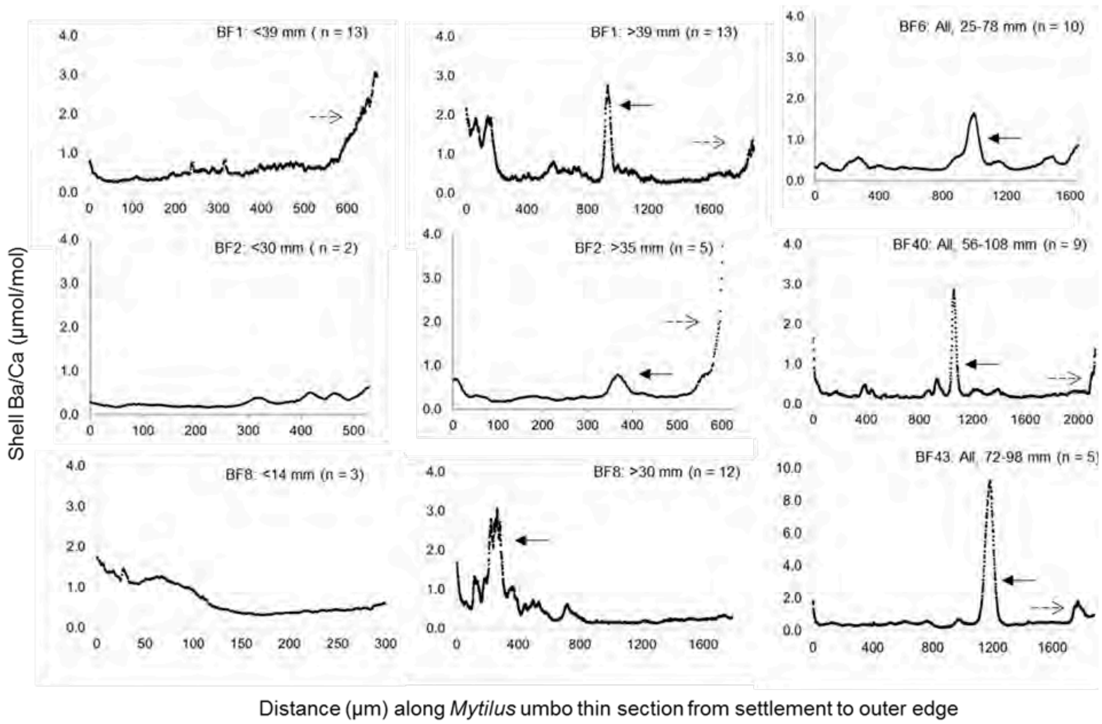

Fig. 5 Representative Ba/Ca profiles across the umbo growth axis for Mytilus *from selected JTMD BF items. Note, for BF1 (Misawa Dock 1), BF2 (skiff), and BF8 (Misawa Dock 2) the smaller shells do not display a peak in shell Ba/Ca prior to the gradual increase at the outer shell edge. The solid arrow indicates the initial Ba/Ca peak that is interpreted as occurring in the NW Pacific, potentially related to the tsunami, and the open arrow is interpreted as arrival in NE Pacific coastal waters.*

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) NE 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 ($R^2 > 0.75$; Fig. 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 NE 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.

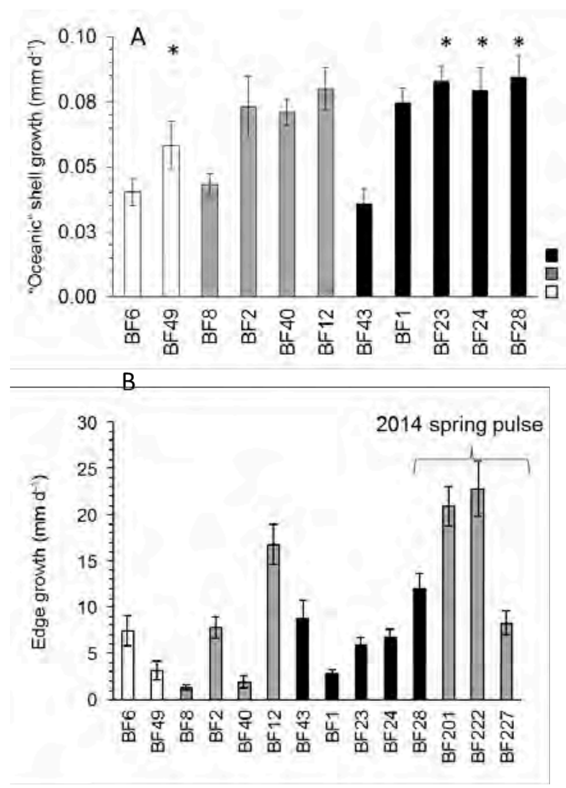

Fig. 6 Right: (A) Mean (±2 SE) "oceanic" shell growth of Mytilus *based on chemical (Ba/Ca) and structural analysis of shells. Growth was estimated based on an empirical relationship between umbo width to total shell length for each debris item. Oceanic growth was defined as all shell deposition prior to gradual elevation of Ba/Ca at the 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 NE 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 NE Pacific coastal waters.*

The JTMD *Mytilus* grew an average of 0.06 ± 0.017 mm/day (mean ±2 SE) during transit and displayed variable shell growth (1 to 23 mm) during coastal residency in the NE Pacific (Fig. 6). Therefore, although slower than growth rates attained in coastal locations or culture settings (~0.12–

0.16 mm/day) (Peteiro *et al*., 2006; Cubillo *et al*., 2012), the JTMD mussels were growing during their oceanic transit and arrived in many locations capable of reproduction after 15 to 40+ months at sea.

In summary, we used the blue 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 North America and Hawaii.

References

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(Continued from page 19)

negotiation targets of COP21. Many data showed a two in three probability that holding warming to 2°C or less will require limiting future carbon dioxide emissions to about 900 billion tons, roughly 20 times the annual emissions in 2014. The time when that emission limit is exceeded is very soon. Optimistic news came from Mr. Fatih Birol, Executive Director of the International Energy Agency, who stated, "*For the first time, energy-related CO_2 emissions stalled despite the global economy expanding 3% in 2014.*" I felt a sense of guilt while writing this report seated in an airplane, watching the jet engine outside of my window. More details can be found in the conference Outcome Statement.

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