Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Transoceanic dispersal of the mussel *Mytilus galloprovincialis* on Japanese tsunami marine debris: An approach for evaluating rafting of a coastal species at sea

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ARTICLE INFO

Keywords:
Biofouling
Invasive mussel
Transport
Growth
Reproduction

ABSTRACT

Biofouled debris from the 2011 Great East Japan earthquake and tsunami has landed in the Northeast Pacific and along the Hawaiian Islands since 2012. As of 2017, > 630 biofouled debris items with > 320 living species of algae, invertebrates, and fish have been examined. The invasive mussel *Mytilus galloprovincialis* was present on > 50% of those items. Size, reproduction, and growth of this filter-feeding species were examined to better understand long-distance rafting of a coastal species. The majority of mussels (79%) had developing or mature gametes, and growth rates averaged 0.075 ± 0.018 SE mm/day. Structural and elemental (barium/calcium) analysis of mussel shells generated estimates of growth in coastal waters (mean = 1.3 to 25 mm total length), which provides an indication of residence times in waters along North America and the Hawaiian Islands prior to landing. Detailed studies of individual species contribute to our understanding of debris as a transport vector and aid efforts to evaluate potential risks associated with marine debris.

1. Introduction

An unexpected outcome of the tragic 2011 Great East Japan earthquake and ensuing tsunami was that many living species of algae, invertebrates, and fish (> 320) were transported > 6000 km on or associated with tsunami-related debris items and made landfall in the Northeast Pacific and along the Hawaiian Archipelago. Although there are numerous known natural and anthropogenic vectors that can transport marine species relatively long distances (Helmuth et al., 1994; Ruiz et al., 1997; Thiel and Haye, 2006; Fraser et al., 2011), there is far less information on marine debris as a transoceanic transport vector for potentially invasive species (Thiel and Gutow, 2005a; Gregory, 2009; Goldstein et al., 2014; Kiessling et al., 2015) and almost no information on tsunami-generated debris (Calder et al., 2014; Carlton et al., 2017). In fact, it was not until June 2012, when a large dock from Misawa, Japan that was torn loose during the tsunami landed on a beach in Oregon with > 100 living species and many 1000s of individuals (Carlton et al., 2017) that the potential for the Great East Japan tsunami to create a flotilla of well-constructed transport vectors was fully recognized.

The magnitude-9 earthquake and resulting tsunami, which were centered off the northeast coast of Honshu, occurred in March, a time when many coastal invertebrates begin to reproduce. There is also evidence that reproduction in some coastal invertebrate species is stimulated by large waves or storm events (Young, 1945; Shanks, 1998). Therefore, the timing and magnitude of these coupled natural disasters created an unusual event that released an exceedingly large amount of available settlement substrata into the coastal ocean during a period of potentially high reproductive effort.

By the end of 2012, it was readily apparent that various types of debris with extensive biofouling that originated from the tsunami were landing from Alaska to California and along the Hawaiian Islands (Carlton et al., 2017). Although marine debris has been identified as a potential vector for invasive species for some time (Barnes, 2002), there is usually little to no information on the debris' provenance, longevity, or sources of larvae. In contrast to other known marine transport vectors, such as ship hull fouling and ballast water (Carlton and Geller, 1993; Sylvester et al., 2011; Lo et al., 2012; Murray et al., 2012), marine debris has certain unique attributes. Ships typically arrive in predictable locations and at measurable frequencies whereas rafted

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http://dx.doi.org/10.1016/j.marpolbul.2017.10.040
Received 18 March 2017; Received in revised form 2 October 2017; Accepted 19 October 2017

Table 1
Japanese Tsunami Marine Debris-Biofouling items (JTMD-BF) included in analysis of the mussel *Mytilus galloprovincialis* transported on JTMD resulting from the 2011 Great East Japan earthquake and tsunami. The JTMD-BF number, type of item, and landing location are included with the mean total length (TL, mm) and standard deviation (SD) and sample size (*n*) of the mussels collected from each item. The method of initial mussel preservation is also included (preserve method: F = frozen; E = ethanol). See Table A1 for sample sizes for the genetic, reproductive, size, and growth analyses.

JTMD BF no.	Type of item	Landing location	Landing date	TL, mm	SD	*n*	Preserve method
1	Dock	Newport, OR	5 Jun 12	42.9	15.3	101	70%F/30%E
2	Vessel	Ilwaco, WA	15 Jun 12	37.9	15.0	79	E
6	Vessel	Oahu, HI	29 Nov 12	55.5	11.7	63	E
8	Large dock	Olympic National Park, WA	18 Dec 12	57.8	21.8	132	10%F/90%E
12	Vessel	Grays Harbor, WA	28 Dec 12	56.4	11.4	19	E
17	Float	Oahu, HI	9 Jan 13	58.0	4.8	7	E
21	Buoy	Kauai, HI	18 Jan 13	55.0	6.6	5	E
23	Vessel	Gleneden Beach, OR	5 Feb 13	51.9	12.6	78	F
24	Pallet	South Beach, OR	8 Feb 13	66.7	11.9	26	F
28	Vessel	Horsfall Beach, OR	20 Feb 13	59.2	11.7	29	86%F/14%E
29	Vessel	Clatsop Beach, OR	27 Feb 13	67.2	9.0	39	F
31	Rope	Oahu, HI	4 Mar 13	77.0	10.0	3	E
39	Vessel	Cannon Beach, OR	21 Mar 13	64.7	16.5	17	F
40	Vessel	Long Beach, WA	22 Mar 13	71.5	17.8	63	E
43	Vessel	Lincoln City, OR	7 Apr 2013	76.2	10.8	27	E
48	Post & Beam Wood	Nye Beach, OR	14 Apr 13	58.4	11.2	8	E
49	Fish tote	Oahu, HI	29 Mar 13	52.0	7.9	28	E
58	Vessel	Clatsop Beach, OR	30 May 13	74.0	8.6	13	F
131	Vessel	Tokeland, WA	13 Nov 13	63.7	8.0	17	F
135	Vessel	Yachats, OR	17 Feb 14	75.2	7.2	18	E
168	Buoy	Long Beach, WA	10 Mar 14	57.8	5.9	36	E
170	Vessel	Long Beach, WA	23 Apr 14	48.3	13.2	5	E
172	Buoy	South Beach, OR	27 Apr 14	51.7	14.2	36	F
176	Post & Beam Wood	South Beach, OR	29 Apr 14	71.9	11.3	19	F
177	Vessel	Ocean Shores, WA	28 Apr 14	65.8	13.8	21	E
201	Vessel	Brian Booth State Park, OR	16 May 14	70.7	10.0	48	F
222	Vessel	Ocean Park, WA	23 May 14	68.4	8.4	47	F
223	Vessel	Seaview, WA	24 May 14	75.5	9.9	45	F
225	Vessel	Strawberry Hill, OR	27 May 14	65.1	11.4	49	F
226	Vessel	Grays Harbor, WA	25 May 14	70.7	8.2	36	F
227	Vessel	Long Beach Peninsula, WA	5 Jun 14	78.7	12.4	39	F
228	Vessel	Long Beach Peninsula, WA	5 Jun 14	63.1	14.2	13	F
229	Vessel	Quinault, WA	6 Jun 14	50.0	11.2	26	F

material, 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 will be substantially reduced on drifting marine debris in comparison with ship hull fouling. Furthermore, marine debris can transport large numbers of adults, rather than larval stages that are more common in ballast water.

The Mediterranean mussel, *Mytilus galloprovincialis* Lamarck, 1819, is a bivalve mollusc that has been transported globally (Carlton, 1999). Native to the Mediterranean Sea, *M. galloprovincialis* has been introduced to the southern hemisphere (New Zealand, Australia, South Africa, Chile), the Northwest Pacific Ocean (Russia, Japan, Korea, and China), and the Northeast Pacific Ocean (British Columbia to Baja California, Mexico, with the apparent exception of Oregon and perhaps northernmost California) (Fofonoff et al., 2016). Dispersal of the Mediterranean mussel can occur via larval transport in ballast water, ship hull fouling, and, as it is commonly cultured, through aquaculture activities. Based on morphological and genetic evidence, we determined that the Mediterranean mussel is one of the most common species arriving on Japanese Tsunami Marine Debris (JTMD), present on > 50% of the debris items examined (Carlton et al., 2017).

Many of the JTMD Mediterranean mussels (hereafter referred to as “mussels”) arrived at relatively large sizes (40 to > 70 mm total shell length) and in apparently good condition in the Northeast Pacific and along the Hawaiian Islands. We determined the size, reproduction, and growth of this coastal filter-feeding species to better understand factors that contributed to its successful transit across 1000s of km of open water. Our evaluation included the reproductive status and size of mussels on various JTMD items (docks, pallets, totes, and vessels) that made landfall from 2012 to 2014 (living *Mytilus galloprovincialis* continue to arrive on JTMD as of February 2017). We further resolved aspects of the growth and transport history of mussels on a subset of those JTMD items by completing structural and elemental analyses of the shells of representative mussels. Collectively, these observations provide novel and valuable insight on the transport of biota on JTMD and, potentially, marine debris in general and, in theory, ocean rafting over geological time (although we know of no prior reports of *M. galloprovincialis* on rafts from the Western Pacific, whether natural or anthropogenic, arriving in the Eastern Pacific).

2. Materials and methods

2.1. Collection and identification of JTMD mussels

Our initial research focused on documenting and collecting debris items and identifying the associated species, using both morphological and genetic approaches. Specific debris items were classified as Japanese Tsunami Marine Debris (JTMD) based on evidence as reviewed in Carlton et al. (2017). Briefly, we considered an item to be JTMD if it had clear (1) identification, such as a serial or registration number that was linked to an object lost during the tsunami of 2011, or (2) biological evidence of originating primarily from the Tohoku coast of Japan. As of March 2017, > 660 debris items have been intercepted, examined for biota, and classified as JTMD; each item was assigned a unique identification number preceded by JTMD-BF# (Japanese Tsunami Marine Debris - BioFouling#; see Carlton et al., 2017 for a register of JTMD-BF objects by type, landing site, and date).

Partnerships with numerous local, state, federal, and provincial representatives as well as non-governmental organizations and many,