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ADRIFT in the North Pacific: The movement, surveillance, and impact of Japanese tsunami debris

The Great East Japan Earthquake on March 11, 2011 was a devastating event; at a magnitude 9.0, it was the most powerful known to have hit Japan in recorded history. The earthquake created a massive tsunami that impacted more than 10,000 square kilometers of coastline. More than 18,000 people were killed and another 6,000 injured. The tsunami destroyed nearly 300,000 buildings and damaged over 1,000,000 more. As a result, millions of tons of materials were washed into the Pacific Ocean.

Within a year, Japanese Tsunami Marine Debris (JTMD), as it came to be known, began arriving on the shores of the Pacific coast of North America and the Hawaiian Islands carrying living coastal Japanese species (Carlton et al. 2018; Fig. 1). To better understand and characterize the consequences of this unprecedented event, researchers from multiple scientific disciplines came together to document and evaluate the potential impacts from JTMD and associated non-indigenous species (NIS) to coastal ecosystems in North America. Entitled ADRIFT (Assessing Debris Related Impact From Tsunami), the project focused on three major themes: 1) forecasting and hindcasting JTMD trajectories and landings; 2) surveillance and detection of JTMD, and 3) characterizing and assessing the invasion risk of NIS transported on JTMD.

A suite of particle tracking models was developed to simulate the movement of various types of marine debris arising from the tsunami. **Maximenko et al. (this issue)** developed, refined, and calibrated these models using observational reports of debris with different windage to forecast the distribution of various JTMD objects (*e.g.*, polystyrene, wood, vessels) and timelines of their arrival in North America and the Hawaiian Archipelago. These new techniques allowed estimation of the oceanographic conditions along probable pathways of individual items, the trajectories of which are critical to determining the survival of NIS on JTMD.

The arrival of JTMD was documented by opportunistic encounters and ongoing dedicated shoreline debris monitoring programs. The temporal and spatial variability in JTMD landfall in North America and Hawaii was analysed by **Murray et al. (this issue)** and showed that in the years following the tsunami, beached debris increased by at least a factor of 10 over baseline levels. A novel webcam installation on an Oregon beach provided additional insights into the refloating of debris from shorelines and is a useful tool for monitoring marine debris in general (**Kako et al. this issue**). When combined with oceanographic models, it appears that a substantial amount of low to medium windage JTMD washed ashore in Washington State, Oregon, Vancouver Island and the central coast of British Columbia. Alaska and northern British Columbia received large amounts of higher windage objects relatively quickly following the tsunami (Murray et al., this issue; Clos-Versailles 2016).

Recognizing the existence of vast, uninhabited shorelines where JTMD could have made landfall, aerial surveys were conducted to search for JTMD on the coastlines of British Columbia (**Kataoka et al. this issue**) and the main Hawaiian Islands (**Moy et al. this issue**). These surveys provide important baselines of marine debris and were the first comprehensive debris evaluation in these two regions following the tsunami, and complementing previous similar efforts in Alaska. Aerial images are made available for other researchers and managers to use through publicly-accessible online sources (BC Data Catalogue, 2016; Hawaii DLNR 2015). An image analysis technique was developed to quantify marine debris abundance with high spatial resolution using archived aerial photographs (**Kataoka et al. this issue**). In both British Columbia and the Hawaiian Islands, the orientation of shorelines and prevailing wind conditions combine to produce debris “hot spots.”

The invasion potential of species associated with JTMD was examined by 1) documenting biodiversity associated with arriving JTMD objects, and 2) formally evaluating both the risk of the species and JTMD as a vector for NIS overall. Over 630 JTMD items were intercepted and sampled, from which approximately 370 species of invertebrates, algae, and fish have been identified (Carlton et al. 2017; Hanyuda et al. (**this issue**); Hansen 2017a,b,c). Remarkably, at least seven new species of marine invertebrates and algae have been detected and described from JTMD (Carlton et al. 2018). Many invertebrate and algal species rafting on JTMD were able to grow and reproduce, despite the relatively low productivity open ocean habitats much of the JTMD appears to have passed through (*e.g.*, Polovina et al. 2001). **Miller et al. (this issue)** examined the growth and reproduction of the mussel *Mytilus galloprovincialis* arriving with JTMD items and found that the majority of these individuals grew while at sea and were reproductive upon arrival in the Central and Eastern Pacific. **Lindstrom et al. (this issue)** documented the possible introduction of an algal species *Pyropia* sp. to the central coast of British Columbia and hypothesized its connection with JTMD.

Genetic analyses indicate that most JTMD macroalgae had haplotypes either identical or very closely related to populations in the Tohoku region of Japan that was affected by the tsunami. Hanyuda et al. (**this issue**) applied molecular techniques to determine the source localities of select algal species and ruled out secondary settlement from elsewhere in the Pacific. The influx of new genetic material for many

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Fig. 1. The connections between the Japan coastlines affected by the 2011 tsunami and the debris items sampled on the coasts of North America and Hawaii. Pictured at left is the town of Minamisanriku, Miyagi Prefecture, Japan five years after the tsunami, and at right is one of the researchers (J. Carlton) collecting biological samples from a piece of marine debris in Hawaii.

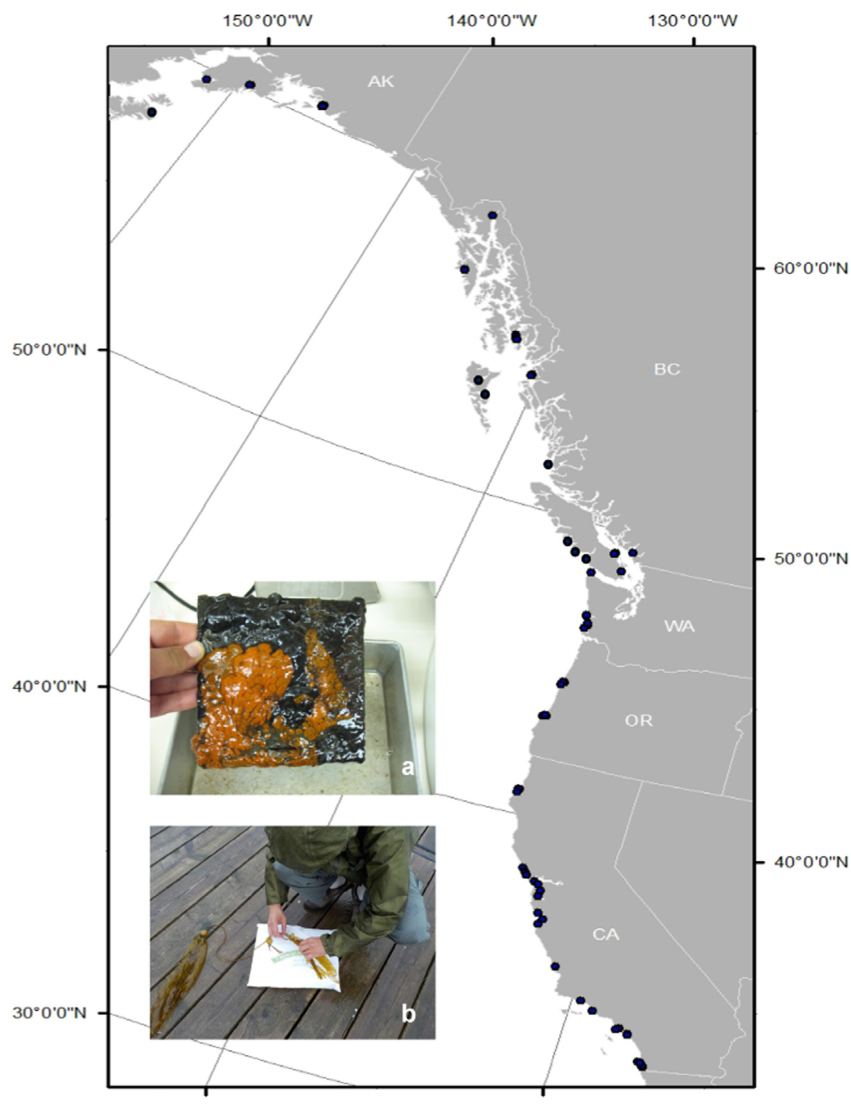

Fig. 2. Baseline surveys to document marine biodiversity were conducted at more than 130 sites in the Eastern North Pacific (dots) for invertebrates (inset a) and algae (inset b).

species may pose an added risk to native ecosystems in North America even where some of these Japanese species had been previously introduced by other, more traditional, invasion vectors.

Using a screening-level risk assessment tool (CMIST – Canadian Marine Invasive Screening Tool; Drolet et al. 2016) for 132 JTMD invertebrates, higher-risk species (some well-known global invaders) were identified for each Pacific North American and Hawaiian ecoregion that received debris (**Therriault et al. this issue**). Overall, risk varied by region, with the highest average risk to Northern California, an area that already hosts a number of NIS from historical vectors such as shellfish aquaculture and commercial shipping (Ruiz et al. 2011). The Hawaiian Islands had the highest cumulative risk, which because of its unique flora and fauna would be potentially subjected to the largest number of novel JTMD species. The life history and tolerance traits of JTMD species were investigated by **Miller et al. (this issue b)** and used to assess the potential impact for relatively unknown species. More than 30 species associated with JTMD have traits similar to those with known invasion histories, and may pose additional risks.

Based on this extensive 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 amount of marine debris arrived on the shores of North America and the Hawaiian Islands between 2012 and 2017 that can be directly attributed to this 2011 megapulse event. An unknown amount of JTMD remains afloat in the North Pacific Ocean and may continue to arrive for years to come. Living Japanese organisms began arriving with JTMD within a year of the tsunami and continued to arrive as recently as spring 2018 (J.T. Carlton, personal communication). The long lag time between arrival and possible invasion means that sustained monitoring is required for JTMD species on the coastlines of North America and the Hawaiian Islands. Initial baseline surveys were conducted at more than 130 sites in the Eastern North Pacific in 2014-2016 (Fig. 2). Fouling panels were used to document marine invertebrate diversity, timed walks documented marine algae diversity, and native mussel samples were targeted to look for parasites and pathogens. These surveys form an important record of the diversity present soon after the arrival of debris and can be used to compare in the event of any possible future invasion. Disentangling introductions attributed to tsunami debris will be complicated by the presence of vectors, such as commercial shipping, recreational boating, and the aquarium and bait trades, that continue to operate (Fowler et al 2016; Bailey 2015; Clarke Murray et al 2011; Padilla and Williams 2004). Increasing quantities of marine debris around the globe combined with more frequent large storm events may intensify the risk of marine rafting invasions in the future.

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