Executive Summary

The Great East Japan Earthquake, with magnitude 9.1, struck off the Tohoku coast on March 11, 2011, and triggered a massive tsunami that surged inland across kilometers of shoreline. This event was a natural disaster of staggering proportions, causing loss of human life, property destruction, and environmental damage. The tsunami washed millions of tons of material into the Pacific Ocean and, within a year, this debris (termed Japanese Tsunami Marine Debris or JTMD), carrying living coastal Japanese species, began arriving on the shores of the Pacific coast of North America and the Hawaiian Islands (hereafter Hawaii). The overall goal of a 3-year (2014–2017) PICES project, funded by the Ministry of the Environment (MoE) of Japan, was to assess and forecast the potential effects of JTMD, especially those related to non-indigenous species (NIS), on ecosystem structure and function, the coastlines, and communities along the Pacific coast of North America and Hawaii, and to suggest research and management actions to mitigate any impacts.

The JTMD study provided the first opportunity in the history of marine science to track a multi-year large-scale (7000+ km) transoceanic rafting event of marine life originating from an exact known source and with an exact known sea-entry time. The project, referred to as ADRIFT (**A**ssessing the **D**ebris-**R**elated **I**mpact **F**rom the **T**sunami), brought together researchers from multiple scientific disciplines, and this international team focused on three major themes: (1) modeling movement of marine debris in the North Pacific to forecast and hindcast JTMD trajectories and landings, (2) surveillance and monitoring of JTMD landfall and accumulation, and (3) characterizing and assessing the invasion risk of NIS transported on JTMD.

The *modeling group* employed a suite of five general circulation models, validated and scaled using available observational reports, to simulate the movement of marine debris and to forecast the distribution of JTMD and timelines of its potential arrival on the Pacific coast of North America and in Hawaii. Model solutions suggest that during the eastward drift across the North Pacific the debris is "stratified" by the wind such that light-weight floating debris (e.g., polystyrene materials) is transported rapidly, sometimes reaching North America within a year following the tsunami, while heavier partially submerged or sunken debris could remain in the ocean considerably longer, with the potential to become trapped in the part of the Subtropical Gyre known as the "garbage patch." Model predictions agree with the types of JTMD reported from different areas and timelines of its arrival on the North American and Hawaiian coasts, exhibiting strong seasonal and interannual variations. New modeling techniques were also developed to derive probable drift trajectories of individual JTMD items to highlight areas where debris was likely to accumulate, and to evaluate the oceanographic conditions (temperature, salinity, etc.) along the JTMD pathways where Japanese coastal species could potentially survive transit, and thereby facilitating NIS risk assessments.

Analysis of the temporal and spatial variability in JTMD landfall in North America and Hawaii by the *surveillance and monitoring group* demonstrated a sharp and significant increase in debris influx beginning in May 2012; the detection of indicator items, such as beverage containers and other consumer objects, suggested a 10-fold increase in beached debris over pre-tsunami levels. It was also found that debris influx differed by coastline, with higher-windage debris being transported to higher

latitudes. Recognizing the existence of vast, uninhabited areas where JTMD could have made landfall, systematic aerial photographic surveys were conducted to search for, and quantify, JTMD arriving on the coastlines of British Columbia (BC) and Hawaii. The surveys were the first comprehensive debris evaluations in these two regions, providing an important baseline of marine debris and complementing previous similar efforts in Alaska. In February 2015, a webcam system was installed at a site in Oregon to track beach-specific debris landings and removals to better understand the temporal dynamics of debris on coastal beaches.

The *NIS group* examined the invasion potential of species associated with JTMD by documenting the biodiversity allied with arriving JTMD objects, formally evaluating the risk of the species and JTMD as a vector for NIS overall, and by conducting detection surveys in Pacific North America and Hawaii. Since the summer of 2012, over 630 JTMD items were intercepted and sampled, from which more than 370 species of algae, invertebrates and fish have been identified. Surprisingly, many species rafting on JTMD grew while at sea and had the potential to be reproductive upon arrival on the coasts of Hawaii and the Eastern Pacific. With time, fewer species arrived alive, but even as of spring 2017 living Japanese species were still documented arriving on JTMD objects.

The invasion risk of species associated with JTMD was characterized using a screening-level risk assessment tool – the Canadian Marine Invasive Screening Tool (CMIST). Higher-risk invertebrates (some well-known global invaders) were identified for each Pacific North American and Hawaiian ecoregion (unique biogeographic areas with different species composition) that received debris. Overall, risk varied by region, with the highest median risk given to northern California (an area that already hosts a number of NIS from historical vectors such as shellfish aquaculture and commercial shipping) and the highest cumulative risk given to Hawaii (an area that has the largest number of novel JTMD species because of its unique flora and fauna). A Top 10 Watch List was produced for each ecoregion. By synthesizing life history and tolerance traits for JTMD species, it was found that more than 30 relatively unknown Japanese species have traits similar to those with prior invasion histories, and may pose additional risks.

Detection surveys (fouling panel deployment, mussel parasite screening and visual inspections) were carried out at more than 130 sites in each affected ecoregion in an effort to detect the establishment of invertebrate and algae species associated with JTMD. These surveys conducted through to 2017 have not detected a single establishment event but are serving as important baselines for future monitoring efforts as NIS introductions can take years to decades to detect.

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 substantial amount of debris arrived on the Pacific shorelines of North America and Hawaii from 2012 to 2017 that can be directly attributed to this event. An unknown portion 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 object types, species composition, and trajectories of JTMD differ in many ways.

The biodiversity of Japanese coastal species documented on recovered JTMD items was diverse. This has been the most intensely scrutinized group of species, with more than 80 taxonomists contributing to the identification effort. Overall, there is little doubt that JTMD represents a novel transport vector for potentially invasive species to North America and Hawaii. However, given its one-time nature, JTMD could be considered a lower risk when compared to other historical and contemporary ongoing vectors like commercial shipping, where the cumulative risk is substantially higher. Nevertheless, JTMD served to significantly raise global awareness of the potential role of marine debris in species dispersal.

The ADRIFT project produced a remarkable number of publications and legacy products. To date, key publications (all Open Access) include: a synthesis of the JTMD vector in *Science* (September 2017, Vol. 357, No. 6358, pp. 1402–1406)[1] and two journal special issues – one with papers focused on the taxonomy of JTMD species published in *Aquatic Invasions* (February 2018, Vol. 13, Is. 1, pp. 1–186)[2], and the other with papers on modeling, surveillance, monitoring, ecology and invasion risk of species published in *Marine Pollution Bulletin* (July 2018, Vol. 132, pp. 1–106)[3].

The following legacy products from the project are available to the scientific community and public:

(1) *The JTMD species database*[4] on the Smithsonian Institution online portal NEMESIS (National Exotic Marine and Estuarine Species Information System) provides information on the distribution, biology, ecology, life history traits and invasion history for selected species of marine invertebrates and algae from the northwestern Pacific Ocean, including those associated with JTMD, and is an important resource contributing to risk assessments;

(2) *The archival collection of marine invertebrate specimens from JTMD* housed at the Royal British Columbia Museum (Victoria, Canada) and *the archival collection of JTMD algae* residing at the Oregon State University Herbarium (Corvallis, USA) allow researchers world-wide to access these unique resources now and in the years to come, especially with the advance of new analytical techniques;

(3) *Products (photographs, debris ranking segments and maps) from the 2014 and 2015 aerial surveys of the exposed outer coast of British Columbia* can be accessed through an online mapping portal designed and hosted by the BC Provincial Government (PICES Tsunami Debris Aerial Photo Survey)[5];

(4) *Imagery and maps from the 2015 aerial survey of the eight main Hawaiian Islands* can be accessed through ArcGIS Story Map[6], and through the State of Hawaii Office of Planning Service Directory[7]; and

[1] https://science.sciencemag.org/content/357/6358/1402
[2] http://www.aquaticinvasions.net/2018/issue1.html
[3] https://www.sciencedirect.com/journal/marine-pollution-bulletin/vol/132/suppl/C
[4] http://invasions.si.edu/nemesis/jtmd/index.jsp
[5] http://catalogue.data.gov.bc.ca/dataset/pices-tsunami-debris-aerial-photo-survey-map
[6] http://arcg.is/29tjSqk
[7] http://geodata.hawaii.gov/arcgis/rest/services/SoH_Imagery/Coastal_2015/ImageServer

(5) An "*Identification guide of seaweeds on Japanese tsunami debris*" available on the Kobe University website[8]; and morphological documentation on "*Benthic marine algae on Japanese tsunami marine debris*" accessible through Oregon State University's online library[9] have been prepared to assist the user in detecting JTMD algal species in the Eastern North Pacific.

The ADRIFT science team considers it essential to share information from the project with the scientific community and the general public on both sides of the Pacific. This has been done not only through publications in peer-reviewed journals, reports, newsletters, and conference presentations, but through outreach activities such as lectures and seminars for university and grade school students, special public events and exhibitions, and numerous media interviews. Two special outreach products highlighting the project's purpose and findings for the general public are an ADRIFT Factsheet – a colorful brochure (in English and in Japanese) distributed in printed form and through the PICES website[10], and an ADRIFT Videoscribe – a 4-minute narrated animation posted on YouTube[11].

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[8] http://www.research.kobe-u.ac.jp/rcis-kurcis/KURCIS/FieldGuide2017may14LR.pdf

[9] https://ir.library.oregonstate.edu/

[10] https://meetings.pices.int/publications/other/ADRIFT-Factsheet-English.pdf

[11] https://www.youtube.com/watch?v=_OUCLMdyIlU&feature=youtu.be