THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

DOI

http://dx.doi.org/10.5670/oceanog.2012.55

Journey to the Center of the Gyre

THE FATE OF THE TOHOKU TSUNAMI DEBRIS FIELD

BY AMAL BAGULAYAN, JINAE N. BARTLETT-ROA, AMANDA L. CARTER, BRYCE G. INMAN, ERIC M. KEEN, ERIC C. ORENSTEIN, NASTASSIA V. PATIN, KIRK N.S. SATO, ELIZABETH C. SIBERT, ANNE E. SIMONIS, AMY M. VAN CISE, AND PETER J.S. FRANKS

INTRODUCTION

The 9.0 magnitude Tohoku earthquake that struck off the coast of Japan on March 11, 2011, was the fourth largest earthquake in recorded history and the largest ever to hit a densely populated region (Bertero, 2011; Lekkas et al., 2011). The ensuing tsunami inundated an area of about 561 km^2 (Geospatial Information Authority, 2011), washing away an estimated 24.9 million tonnes of debris, including wood, sediments, plastics, industrial chemicals, and structural components (Oh, 2011). Two weeks following the tsunami, the meltdown of the Fukushima Daiichi nuclear reactors released radioactive elements into the atmosphere and coastal waters. Atmospheric deposition was found to be an important source of radioactivity in surface waters and may have contaminated the debris field, although the extent of this contamination remains unknown (Buesseler et al., 2012; Honda et al., 2012).

Here, we follow the debris field along its predicted path from its source in Japanese coastal waters through the Kuroshio-Oyashio Extension, the North Pacific Current, and the California Current. From there, it will loop back toward the Hawaiian Islands, ultimately accumulating in the North Pacific Gyre (International Pacific Research Center, 2011b; Figure 1). Relying on precedents from previous natural disasters and ongoing observations, we attempt to predict the impact of this debris field on marine and coastal ecosystems in each of these regions. We predict that the Tohoku debris field will create a rare perturbation for ecosystems interconnected across the North Pacific, exacerbating the accumulating human impacts on the world ocean.

COASTAL JAPANESE WATERS

Chemical contaminants and debris were carried over Japan's narrow eastern continental shelf, home to a multibillion-dollar fishing industry (Johnson, 2011), passing through habitats for plankton, benthic invertebrates, fish larvae, and many transitory pelagic fish. Seafloor observations by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) suggested that receding waves kept nearshore bays, coves, and offshore trenches relatively clear of debris (K. Fujikura and H. Kitazato, JAMSTEC, *pers. comm.*, Nov. 23, 2011). Larger objects may have scoured swaths of the continental shelf as they were carried offshore.

The nuclear fission reactor meltdowns at Fukushima Daiichi released radioactive isotopes with ecologically relevant half-lives, such as cesium-134 (2 yr), cesium-137 (30 yr), and strontium-90 (29 yr) (Kaeriyama et al., 2008; Hong et al., 2011). A large amount of iodine-131, known to cause thyroid cancer in humans (Morita et al., 2010), was also introduced. Due to iodine's short half-life (8 d), its ecological impact is presumed to be minimal and geographically restricted. Strong nearshore currents advected radioactively contaminated water northeastward into the open Pacific, but the Kuroshio Current acted as a boundary to more southerly exchange (Buesseler et al., 2012). Some of the radioactive elements were also released into the atmosphere, where they could have travelled significant distances before deposition (Honda et al., 2012).

Elevated levels of radiation found in fish samples led the Japanese government to institute a local moratorium on fishing that was still in place as of May 2012 (Institute of Electrical and Electronics Engineers, 2012). Although this moratorium addressed short-term contamination, long-lived radioactive isotopes could be incorporated into sediment, phytoplankton, and brown algae, eventually bioaccumulating in higher trophic levels such as copepods, molluscs, polychaetes, and fishes, all of which are directly or indirectly consumed by humans harvesting from coastal waters (Gadd, 1999; Heldal et al., 2001; Burger et al., 2006; Kaeriyama et al., 2008; Morita et al., 2010; Hong et al., 2011). The radioactive signature of the Fukushima Daiichi disaster could persist locally for the life of the isotopes, as contaminated sediments are remobilized through physical processes, chemical changes, and biological activity (Fisher et al., 1991; Vives i Batlle, 2011).

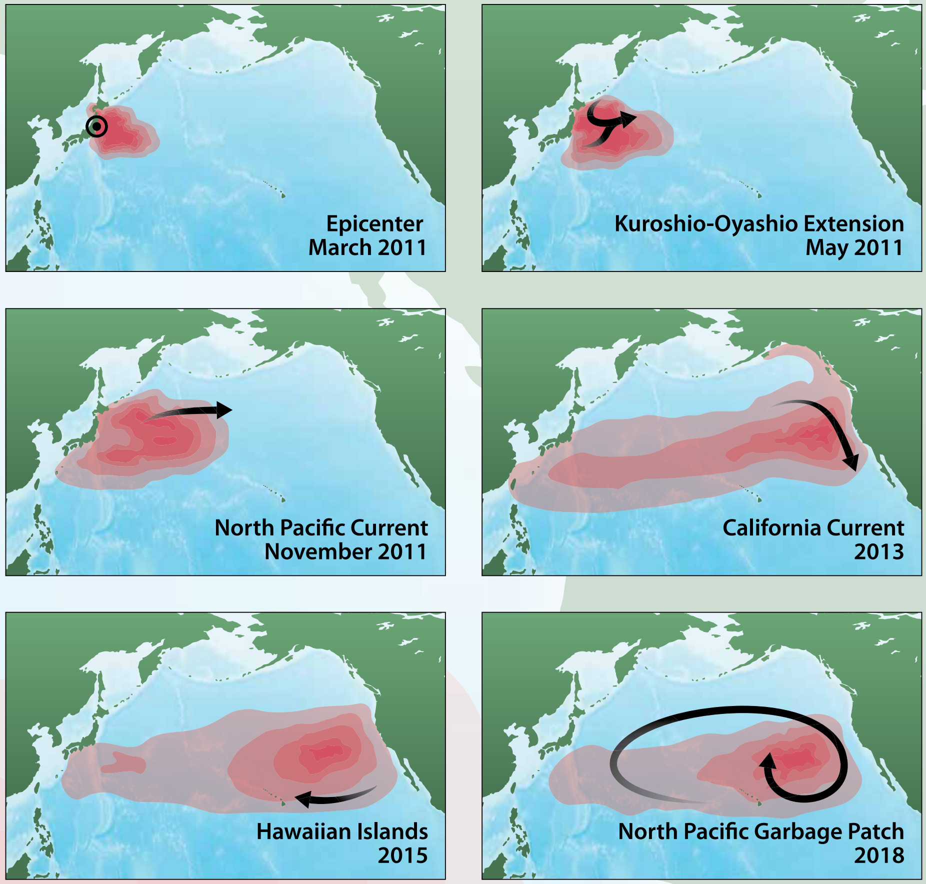

Figure 1. The projected path of the Tohoku tsunami debris field showing the expected arrival time of debris at each major geographic area covered in this review. Darker shades represent increasing probability of debris occurrence. Debris path adapted from IPRC (2011b). Bathymetry modified from an image by Hiroyasu Hasumi, University of Tokyo.

KUROSHIO-OYASHIO EXTENSION

Within a month, the debris field entered the productive waters of the Kuroshio-Oyashio Extension (KOE) region, a major confluence of Pacific western boundary currents. This timing corresponded with the annual spring phytoplankton bloom that governs ecosystem dynamics across the North Pacific (Figure 2; Saito et al., 2002; Liu et al., 2004).

Following a tsunami, primary productivity may increase in response to nutrient loading. For example, immediately following the 2004 Indian Ocean tsunami, nutrients and phytoplankton increased near the earthquake's epicenter (Murty et al., 2007; Satheesh and Wesley, 2009; Yan and Tang, 2009). Our analyses of MODIS satellite data from the KOE between 2003 and 2011 (http://oceancolor.gsfc.nasa.gov/cgi/l3) suggest that the 2011 spring phytoplankton bloom initiated earlier in the year (March, rather than early April), and was significantly higher (*t*-test, 2460 df, $p << .001$) for that month than in any other year since 2003 (Figure 2). This circumstance may have been a consequence of increased nutrient input from the tsunami, due either to deep mixing or terrestrial runoff.

Though the KOE extends far offshore, radioactive elements can be introduced

Amal Bagulayan, Jinae N. Bartlett-Roa, Amanda L. Carter, Bryce G. Inman, Eric M. Keen, Eric C. Orenstein, Nastassia V. Patin, Kirk N.S. Sato, Elizabeth C. Sibert, Anne E. Simonis, *and* **Amy M. Van Cise** *are students in the biological oceanography class SIO280, and* **Peter J.S. Franks** *(pfranks@ucsd.edu) is Professor, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA.*

into these waters by atmospheric transport and subsequent deposition. This process could explain the high levels of cesium-137 in samples gathered several hundred kilometers offshore of Japan (Buesseler et al., 2012). Radionuclides in suspended solids and zooplankton were up to two orders of magnitude higher than background levels, demonstrating that bioaccumulation is already occurring (Honda et al., 2012).

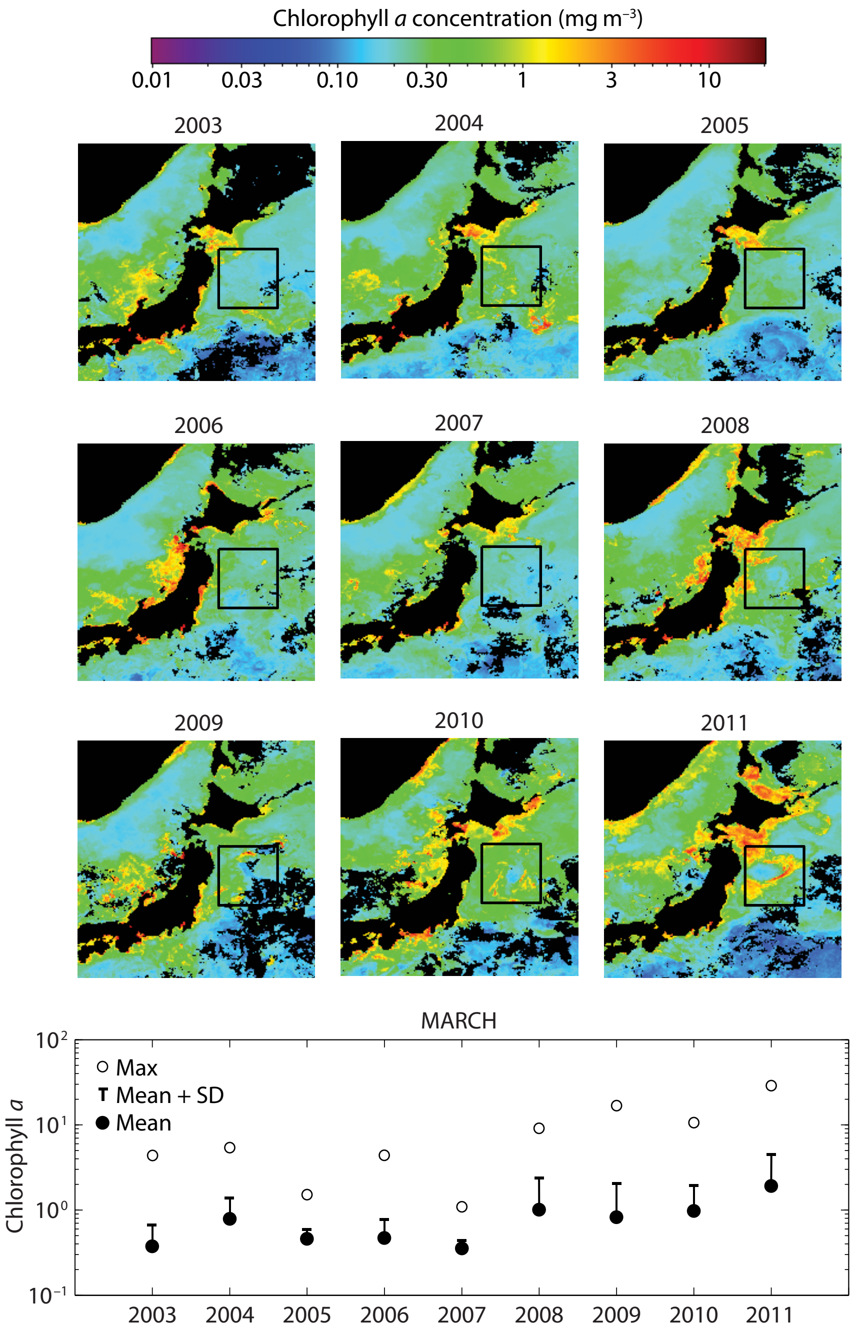

Figure 2. Satellite remotely sensed chlorophyll 2003–2011. Upper panels: March-averaged MODIS satellite surface chlorophyll data from near Japan. Black areas are either land or cloud-covered. Lower panel: Mean, mean + standard deviation, and maximum chlorophyll *a* value from the boxed region in each satellite image.

By May, debris of several types entered the KOE spawning grounds of many commercially important fisheries. For example, the larvae of sardine (*Sardinops melanostictus*), saury (*Cololabis saira*), anchovy (*Engraulis japonicus*), and tuna (*Thunnus* spp.) grow in the KOE as they are carried eastward (Zainuddin et al., 2006; Watanabe, 2009). Larvae aggregate around floating mats of kelp, wood, or other debris (Fonteneau et al., 2000), which could improve survival rates and provide a short-term boost in the vitality of depleted fisheries. However, species aggregating around the debris may suffer after ingesting—or through direct exposure to—leached chemicals. This situation may result in decreased egg development or hatch rate, disruption of metabolic and endocrine pathways, or death (Hardy et al., 1987; Oehlmann et al., 2009). Chemicals and small floating plastics typically concentrate within a microlayer at the air-sea interface (von Westernhagen et al., 1987; Mato et al., 2001) where the majority of buoyant eggs and larvae occur. As pollutant-exposed larvae and juveniles are preyed upon, chemical concentrations may bioaccumulate and compound deleterious effects (Ueno et al., 2003). While this is already occurring at steadily increasing levels in marine systems, anomalous inputs like the debris field can have a punctuating effect.

NORTH PACIFIC CURRENT

By late summer 2011, the debris field exited the KOE and entered the eastward flow of the North Pacific Current (NPC), located between 40° and 50°N (Figure 1). Model predictions of the movement of the debris field were confirmed in September 2011, when a Russian vessel encountered debris about 1,100 km north of Midway Atoll (28°N, 177°W). The debris included large and small buoys from fishing nets, wooden boards, drums, and at least one fishing vessel from the Fukushima Prefecture (International Pacific Research Center, 2011a). Much of the debris is expected to be fishing gear from the > 26,000 fishing boats that were lost in the tsunami (Ministry of Agriculture, Forestry and Fisheries, 2011). "Ghost fishing" by lost gear presents a significant entanglement hazard to animals that gather near debris (Brown and Macfadyen, 2007).

The NPC serves as a migratory corridor for commercially important fishes, most notably bluefin, yellowfin, bigeye, and skipjack tunas (*Thunnus* spp.) (e.g., Food and Agriculture Organization, 2011). As adults, these species occupy overlapping regions of the Pacific, with bluefin tuna migrating across the basin several times annually (Figure 3; Block et al., 2011). This migration pattern suggests that, of these species, bluefin tuna may be most susceptible to debris-related impacts in the NPC.

Over 50% of the world's haul of tropical tunas is caught by targeting Fish Aggregating Devices (FADs), floating debris that is a natural attractor for some fishes (Girard et al., 2004). FAD-based fishing using purse seines catches younger individuals, in contrast to longline sets that primarily catch adults (Fonteneau et al., 2000). Because the debris field effectively increases the number of FADs, focused fishery effort on them may result in overfishing of juveniles, which may reduce the breeding stock.

As timber from ~ 400,000 destroyed buildings transits the Pacific Ocean, it will become water-logged and sink at varying rates, some landing on the seafloor within the NPC and some reaching the California Current (National Police Agency of Japan Emergency Disaster Countermeasures Headquarters, 2012). As wood sinks, the potential habitat of wood-fall and opportunistic species may increase dramatically (Gooday, 2002). Some bivalves, crustaceans, and polychaetes may benefit from the increased abundance of wood falls (Kiel and Goedert, 2006; Bernardino et al., 2010). Though certain early colonizing bivalves recruit poorly on the copper-treated lumber typical of Japanese construction (Japan Wood Preserving Association, 2012), wood-boring crustaceans may be uninhibited by the preservatives (Distel, 2003). The abundance and composition of the sunken debris could cause atypical successions and community compositions that may last a decade or more.

CALIFORNIA CURRENT SYSTEM

Debris transported across the Pacific by the NPC is ultimately transferred to coastal currents along western North America, either the smaller, poleward-flowing Alaska Current or the California Current System (CCS), which moves south along the Washington, Oregon, and California coasts (International Pacific Research Center, 2011b; Showstack, 2011). In addition to being a productive region characterized by seasonal upwelling, the CCS is a common ground for many pelagic predators, and many trans-Pacific migratory pathways converge within its waters (Block et al., 2011). Already, within one year of the tsunami, fishing floats, nets, and plastics identifiable as coming from Japan have washed ashore in Alaska, British Columbia, and Washington—much earlier than simulation models predicted (International Pacific Research Center, 2011b; Maximenko and Hafner, 2012).

The probability of successful invasion along the CCS by a rafting species depends upon the life history of the organisms, the duration and path of transport, and the resilience of the

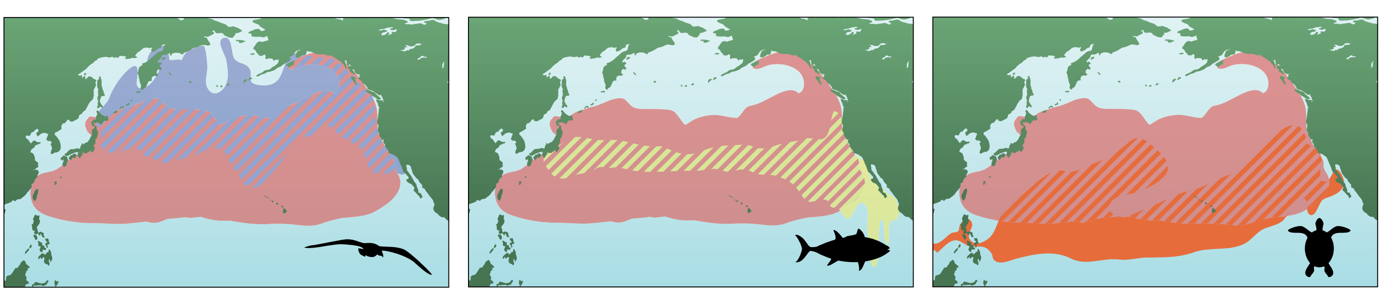

Figure 3. Satellite tracks of migratory tunas (yellow), sea turtles (orange), and seabirds (purple) superimposed upon the projected coverage of the debris field (red). Regions of overlap are crosshatched. *Adapted from Block et al. (2011)*

invaded ecosystem (Thiel and Gutow, 2005). The west coast of North America is recognized as the most invaded region on the continent, primarily in high-traffic ports such as San Francisco (Ruiz et al., 2000), with the most invasive species previously originating from Indonesia (Ruiz et al., 2000; Williams and Smith, 2007). The tsunami debris field may be an unprecedented source of potentially invasive species to the CCS ecosystem, its $500 million fishing industry (National Marine Fisheries Service, 2010), and its associated coastal and benthic habitats.

On the west coast of North America, large woody debris expelled from rivers has been the source of habitat for deep-sea communities (Kiel and Goedert, 2006). In the last century, however, this supply was greatly reduced by human enterprise, especially river damming, deforestation, and the harvest of floating timber (Doloff, 1993; Moulin and Piegay, 2004). This ongoing "deep-sea deforestation" may be temporarily offset by the influx of new—albeit chemically treated—woody habitat from the debris field, thus increasing the biomass of some wood-fall associated species.

HAWAIIAN ISLANDS

The increasingly fragmented debris is predicted to reach the shores of the Hawaiian archipelago four years after the tsunami. Many migratory, endangered, and endemic species rely upon this island chain and will probably be threatened by the influx of debris (Polovina et al., 2001, 2008). The floating wreckage may still contain nonbiodegradable fishing gear from Tohoku that could entangle, injure, and kill large numbers of marine mammals, seabirds, and coral reef communities (Donohue et al., 2001; Chiappone et al., 2005; Brown and Macfadyen, 2007).

> "HERE, WE HAVE PRESENTED A LAGRANGIAN VIEW OF THE TOHOKU DEBRIS FIELD, FROM COASTAL SOURCE TO ABYSSAL SINK, AS IT DRIFTS THROUGH THE ECOSYSTEMS, TROPHIC WEBS, AND WATER COLUMN OF THE NORTH PACIFIC."

The debris may prove to be disastrous for the endangered Hawaiian monk seal (*Monachus schauinslandi*), whose population is already decreasing by 4% annually (Baker et al., 2011; Lowry et al., 2011). With the highest annual entanglement rate among all pinnipeds (Henderson, 2001), this population will likely experience increased mortality caused by the lost fishing gear. Entanglement deaths of the endangered hawksbill turtle (*Eretmochelys imbricata*) of the Northwest Hawaiian Islands have decreased from 20 to one or two annually due to bycatch mitigation (Donohue et al., 2001; Finkbeiner et al., 2011); sadly, the debris may reverse this trend.

Plastics in the debris field may be ingested by a variety of marine mammals and seabirds (Derraik, 2002). Sea turtles (Carr, 1987) and Hawaiian albatrosses (Young et al., 2009) are especially prone to consuming degraded plastic debris that is mistaken for, or aggregated around, their natural prey. Albatross chicks fed plastic parts by their parents can die before ever going to sea; plastics can cause physical trauma and blockages in the digestive tract or reduce the urge to feed, leading to starvation (Young et al., 2009).

NORTH PACIFIC GYRE

The convergence zone of the North Pacific Gyre (NPG) is the predicted final resting place for much of the Japanese tsunami debris field, particularly floating plastics. The gyre's center is home to the North Pacific Garbage Patch, a region where plastics and other floating debris accumulate and persist for decades (Venrick et al., 1973; Rios et al., 2010). It is hypothesized that such material will eventually degrade and lose buoyancy due to biofouling by organisms and sediment (Barnes et al., 2009). However, the time frame of suspension in the water column remains unknown (Ye and Andrady, 1991).

Plastics in the NPG affect fishes, seabirds, turtles, and marine mammals, as well as commercially important fisheries. In addition to the previously mentioned physical effects of intestinal blockage, entanglement, and suffocation that lead to mortality, many chemical effects can be associated with the breakdown of plastic debris. Degrading plastics leach a broad spectrum of chemical additives and also adsorb organic contaminants already present in seawater (Artham and Doble, 2009; Rios et al., 2010). Organisms that ingest plastics, or are associated with contaminated water, may be at risk from the deleterious effects of these chemicals, causing, for example, disruption of endocrine, reproductive, and immune systems, and, potentially, neurobehavioral disorders and cancer (Jones and de Voogt, 1999). While it is too soon to speculate on the impact of these contaminant pathways, these chemicals may persist in the marine environment and, under certain conditions, be transferred to marine organisms (Teuten et al., 2009).

CONCLUSIONS

Here, we have presented a Lagrangian view of the Tohoku debris field, from coastal source to abyssal sink, as it drifts through the ecosystems, trophic webs, and water column of the North Pacific. The international community needs to come together to develop a plan to mitigate the effects of the Tohoku tsunami debris field. Although our predictions are necessarily speculative, some effects are easier than others to identify. For example, while the chemical effects of bioaccumulation are difficult to predict, entanglement from debris may have a negative impact on commercially important and endangered species. Consequently, directed efforts to remove debris around affected islands or coastlines will likely be a worthwhile investment. Additionally, to avoid overfishing of juvenile tunas and other fishes associated with FADs, it is advisable to manage fishing effort in debris-affected areas.

Although its journey makes for a memorable story, within decades, the debris will assimilate into the countless tons of garbage already accumulating in the central North Pacific. While this is an unprecedented influx of debris, the widespread short-term effects will only be a pulse in the rising levels of anthropogenic impacts to the ocean.

ACKNOWLEDGEMENTS

The topic of this paper was assigned as a term project to SIO280, the graduate-level introductory biological oceanography course at Scripps Institution of Oceanography taught by Peter Franks. The 35 students, representing all the disciplines at Scripps, submitted nine group papers that were subsequently synthesized into this paper by the named authors. The remaining 24 authors are J.R. Ballard, M.E. Barron, K.L. Chavarria, J.K. Dhaliwal, D. Niu, A.A. El Gamal, A.L. Freibott, K.A. Furby, J. Guzman Morales, M.D. Johnson, L. Li, B.W. Miller, A.D. Mullen, C.F. Nickels, A.E. Noto, B.D. Queener, S.C. Sanchez, S. Shoffler, S.J. Stevens-Mcgeever, M.F. Tekverk, J.C. Traller, C. Turner, S.J. Wilson, and A.K. Wright. The authors gratefully acknowledge the comments and suggestions from reviewers Kara Lavender Law, Scott Shaffer, and Janet Voight, and the encouragement and support of Ellen Kappel.

REFERENCES

Artham, T., and M. Doble. 2009. Fouling and degradation of polycarbonate in seawater: Field and lab studies. *Journal of Polymers and the Environment* 17:170–180, http://dx.doi.org/10.1007/s10924-009-0135-x.

Baker, J.D., A.L. Harting, T.A. Wurth, and T.C. Johanos. 2011. Dramatic shifts in Hawaiian monk seal distribution predicted from divergent trends. *Marine Mammal Science* 27:78–93, http://dx.doi.org/10.1111/j.1748-7692.2010.00395.x.

Barnes, D.K.A., F. Galgani, R.C. Thompson, and M. Barlaz. 2009. Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of The Royal Society B* 364:1,985–1,998, http://dx.doi.org/10.1098/rstb.2008.0205.

Bernardino, A.F., C.R. Smith, A. Baco, I. Altamira, and P.Y.G. Sumida. 2010. Macrofaunal succession in sediments around kelp and wood falls in the deep NE Pacific and community overlap with other reducing habitats. *Deep Sea Research Part I* 57:708–723, http://dx.doi.org/10.1016/j.dsr.2010.03.004.

Bertero, A. 2011. *The 2011 Tohoku Disaster and the Nuclear Incident at Fukushima: Comparative Review, Historical Analysis and Assessment of the Japanese Nuclear Regime*. Advanced International Law Research Seminar, Hastings College of Law, 37 pp, http://dx.doi.org/10.2139/ssrn.1878263.

Block, B.A., I.D. Jonsen, S.J. Jorgensen, A.J. Winship, S.A. Shaffer, S.J. Bograd, E.L. Hazen, D.G. Foley. G.A. Breed, A.-L. Harrison, and others. 2011. Tracking apex marine predator movements in a dynamic ocean. *Nature* 475:86–90, http://dx.doi.org/10.1038/nature10082.

Brown, J., and G. Macfadyen. 2007. Ghost fishing in European waters: Impacts and management response. *Marine Policy* 31:488–507, http://dx.doi.org/10.1016/j.marpol.2006.10.007.

Buesseler, K.O., S.R. Jayne, N.S. Fisher, I.I. Rypina, H. Baumann, C.F. Breler, E.M. Douglass, J. George, A.M. McDonald, H. Miyamoto, and others. 2012. Fukushima-derived radionuclides in the ocean and biota off Japan. *Proceedings of the National Academy of Sciences of the United States of America* 109(16):5,984–5,988, http://dx.doi.org/10.1073/pnas.1120794109.

Burger, J., M. Gochfeld, D.S. Kosson, C.W. Powers, S. Jewett, B. Friedlander, H. Chenelot, C.D. Volz, and C. Jeitner. 2006. Radionuclides in marine macroalgae from Amchitka and Kiska Islands in the Aleutians: Establishing a baseline for future biomonitoring. *Journal of Environmental Radioactivity* 91:27–40, http://dx.doi.org/10.1016/j.jenvrad.2006.08.003.

Carr, A. 1987. Impact of nondegradable marine debris on the ecology and survival outlook of sea turtles. *Marine Pollution Bulletin* 18:352–356, http://dx.doi.org/10.1016/S0025-326X(87)80025-5.

Chiappone, M., H. Dienes, D.W. Swanson, and S.L. Miller. 2005. Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys National Marine Sanctuary. *Biological Conservation* 121:221–230, http://dx.doi.org/10.1016/j.biocon.2004.04.023.

Derraik, J.G.B. 2002. The pollution of the marine environment by plastic debris: A review. *Marine Pollution Bulletin* 44:842–852, http://dx.doi.org/10.1016/S0025-326X(02)00220-5.

Distel, D.L. 2003. The biology of marine wood boring bivalves and their bacterial endosymbionts. *Wood Deterioration and Preservation* 845:253–271, http://dx.doi.org/10.1021/bk-2003-0845.ch014.

Doloff, C.A. 1993. Large woody debris, fish habitat, and historic land use. Pp. 130–138 in *Biodiversity and Coarse Woody Debris in Southern Forests: Proceedings of the Workshop on Coarse Woody Debris in Southern Forests: Effects on Biodiversity.* J.W. McMinn, and D.A. Crossley, eds, University of Georgia, Athens, GA, October 18–20, 1993. Available online at: http://books.google.com/books/about/Biodiversity_and_coarse_woody_debris_in.html?id=9B3980OPKJIC (accessed November 3, 2011).

Donohue, M.J., R. Boland, C. Sramek, and G. Antonelis. 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: Diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. *Marine Pollution Bulletin* 42:1,301–1,312, http://dx.doi.org/10.1016/S0025-326X(01)00139-4.

Finkbeiner, E.M., B.P Wallace, J.E. Moore, R.L. Lewison, and L.B. Crowder. 2011. Cumulative estimates of sea turtle bycatch and mortality in USA fisheries between 1990 and 2007. *Biological Conservation* 144:2,719–2,727, http://dx.doi.org/10.1016/j.biocon.2011.07.033.

Fisher, N.S., C.V. Nolan, and S.W. Fowler. 1991. Scavenging and retention of metals by zooplankton fecal pellets and marine snow. *Deep-Sea Research Part A* 38:1,261–1,275, http://dx.doi.org/10.1016/0198-0149(91)90026-C.

Fonteneau, A., P. Pallarés, and R. Pianet. 2000. A worldwide review of purse seine fisheries on FADs. Paper presented at Pêche Thonière et Dispositifs de Concentration de Poissons, Caribbean-Martinique. Oct 15–19, 1999, http://archimer.ifremer.fr/doc/00042/15278.

Food and Agriculture Organization of the United Nations: Fisheries and Aquaculture Department. http://www.fao.org/fishery/en (accessed November 29, 2011).

Gadd, G.M. 1999. Fungal production of citric and oxalic acid: Importance in metal speciation, physiology and biogeochemical processes. Pp. 47–92 in *Advances in Microbial Physiology*, vol. 41. R.K. Poole, ed., Academic Press.

Geospatial Information Authority in Japan. 2011. (国土地理院). "津波による浸水範囲の面積(概略値) について (第5報)" (in Japanese). Available online at: http://www.gsi.go.jp/common/000059939.pdf (accessed February 27, 2012).

Girard, C., S. Benhamou, and L. Dagorn. 2004. FAD: Fish Aggregating Device or Fish Attracting Device? A new analysis of yellowfin tuna movements around floating objects. *Animal Behaviour* 67:319–326, http://dx.doi.org/10.1016/j.anbehav.2003.07.007.

Gooday, A.J. 2002. Biological responses to seasonally varying fluxes of organic matter to the ocean floor: A review. *Journal of Oceanography* 58:305–332.

Hardy, J., S. Kiesser, L. Antrim, A. Stubin, R. Kocan, and J. Strand. 1987. The sea-surface microlayer of Puget Sound: Part I. Toxic effects on fish eggs and larvae. *Marine Environmental Research* 23:227–249, http://dx.doi.org/10.1016/0141-1136(87)90020-1.

Heldal, H.E., I. Stupakoff, and N.S. Fisher. 2001. Bioaccumulation of ^{137}Cs and ^{57}Co by five marine phytoplankton species. *Journal of Environmental Radioactivity* 57:213–236, http://dx.doi.org/10.1016/S0265-931X(01)00020-0.

Henderson, J.R. 2001. A pre- and post-MARPOL annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the Northwestern Hawaiian Islands, 1982–1998. *Marine Pollution Bulletin* 42:584–589, http://dx.doi.org/10.1016/S0025-326X(00)00204-6.

Honda, M.C., T. Aono, M. Aoyamo, Y. Hamajima, H. Kawakami, M. Kitamura, Y. Masumoto, Y. Miyazama, M. Takigawa, and T. Saino. 2012. Dispersion of artificial caesium-134 and -137 in the western North Pacific one month after the Fukushima accident. *Geochemical Journal* 46:e1–e9.

Hong, G.-H., T.F. Hamilton, M. Baskaran, and T.C. Kenna. 2011. Applications of anthropogenic radionuclides as tracers to investigate marine environmental processes. Pp 367–394 in *Handbook of Environmental Isotope Geochemistry*. M. Baskaran, ed., Advances in Isotope Geochemistry, Springer-Verlag, Berlin, Germany.

Institute of Electrical and Electronics Engineers. 2012. Special Report: Fukushima and the Future of Nuclear Power. *IEEE Spectrum*. Available online at: http://spectrum.ieee.org/static/mapping-fukushimas-impact-on-japan (accessed May 19, 2012).

International Pacific Research Center. 2011a. *Press Release: Russian Ship Finds Tsunami Debris Where Scientists Predicted*. University of Hawai'i at Manoa, HI. Available online at: http://iprc.soest.hawaii.edu/news/press_releases/2011/pallada_tsunami_debris.pdf (accessed March 5, 2012).

International Pacific Research Center. 2011b. *Press Release: Where Will the Debris from Japan's Tsunami Drift in the Ocean?* University of Hawai'i at Manoa, HI. Available online at: http://iprc.soest.hawaii.edu/news/press_releases/2011/maximenko_tsunami_debris.pdf (accessed May 19, 2012).

Japan Wood Preserving Association. 2012. *Wood Preservation in Japan.* Available online at: http://www.mokuzaihozon.org/english/prsvtn.html (accessed February 27, 2012).

Johnson, R. 2011. *Japan's 2011 Earthquake and Tsunami: Food and Agriculture Implications.* Congressional Research Service, Report 7-5700, Washington, DC, 15 pp.

Jones, K.C. and P. de Voogt. 1999. Persistent organic pollutants (POPs): State of the science. *Environmental Pollution* 100:209–221, http://dx.doi.org/10.1016/S0269-7491(99)00098-6.

Kaeriyama, H., T. Watabe, and M. Kusakabe. 2008. ^{137}Cs concentration in zooplankton and its relation to taxonomic composition in the western North Pacific Ocean. *Journal of Environmental Radioactivity* 99:1,838–1,845, http://dx.doi.org/10.1016/j.jenvrad.2008.08.006.

Kiel, S., and J.L. Goedert. 2006. A wood-fall association from late Eocene deep-water sediments of Washington state, USA. *Palaios* 21:548–556, http://dx.doi.org/10.2110/palo.2005.p05-086r.

Lekkas, E., E. Andreadakis, V. Alexoudi, E. Kapourani, and I. Kostaki. 2011. The Mw=9.0 Tohoku Japan earthquake (March 11, 2011) tsunami impact on structures and infrastructure. National and Kapodistrian University of Athens. Available online at: http://portal.tee.gr/portal/page/portal/teetkm/DRASTHRIOTHTES/EKDHLVSEIS/PROSEXEIS_EKDHLWSEIS/EARTHQUAKE_JAPAN/Tab1/EPS-2.pdf (accessed October 11, 2011).

Liu, H., K. Suzuki, and H. Saito. 2004. Community structure and dynamics of phytoplankton in the western subarctic Pacific Ocean: A synthesis. *Journal of Oceanography* 60:119–137. Available online at: http://www.terrapub.co.jp/journals/JO/pdf/6001/60010119.pdf (accessed May 28, 2012).

Lowry, L.F., D.W. Laist, W.G. Gilmartin, and G.A. Antonelis. 2011. Recovery of the Hawaiian Monk Seal (*Monachus schauninslandi*): A review of conservation efforts, 1972 to 2010, and thoughts for the future. *Aquatic Mammals* 37:397–419, http://dx.doi.org/10.1578/AM.37.3.2011.397.

Mato, Y., T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, and T. Kaminuma. 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science and Technology* 35:318–324, http://dx.doi.org/10.1021/es0010498.

Maximenko, N., and J. Hafner. 2012. Marine debris from the tsunami of March 11, 2011: One year after the disaster. Presentation at the International Pacific Research Center, Honolulu, HI, March 5, 2012. (See http://iprc.soest.hawaii.edu/news/marine_and_tsunami_debris/debris_news.php [accessed May 28, 2012])

Ministry of Agriculture, Forestry and Fisheries, 2011. *The Damages caused by the Great East Japan Earthquake*. Available online at: http://www.maff.go.jp/e/quake/press_110824-2.html (accessed November 27, 2011).

Morita, T., Y. Ohtsuka, K. Fujimoto, Y. Minamisako, R. Iida, M. Nakamura, and T. Kayama. 2010. Concentrations of ^{137}Cs, ^{90}Sr, ^{108m}Ag, $^{239+240}$Pu and atom ratio of ^{240}Pu/^{239}Pu in tanner crabs, *Chionoecetes japonicus* and *Chionoecetes opilio* collected around Japan. *Marine Pollution Bulletin* 60:2,311–2,322, http://dx.doi.org/10.1016/j.marpolbul.2010.09.022.

Moulin, B., and H. Piegay. 2004. Characteristics and temporal variability of large woody debris trapped in a reservoir on the River Rhone: Implications for river basin management. *River Research and Applications* 20:79–97, http://dx.doi.org/10.1002/rra.724.

Murty, T.S., U. Aswathanarayana, and N. Nirupama, eds. 2007. *The Indian Ocean Tsunami*. Taylor & Francis Group, London, 528 pp.

National Marine Fisheries Service. 2010. *Fisheries Economics of the United States, 2009.* NMFS-F/SPO-118. The National Marine Fisheries Service, Silver Spring, MD, 172 pp.

National Police Agency of Japan Emergency Disaster Countermeasures Headquarters. 2012. *Damage Situation and Police Countermeasures Associated with 2011 Tohoku District*. Available online at: http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf (accessed February 27, 2012).

Oehlmann, J., U. Shulte-Oehlmann, W. Kloas, O. Jagnytsch, I. Lutz. K.O. Kusk, L. Wollenberger, E.M. Santos, G.C. Paull, K.J.W. Van Look, and C.R. Taylor. 2009. A critical analysis of the biological impacts of plasticizers on wildlife. *Philosophical Transactions of the Royal Society B* 364:2,047–2,062, http://dx.doi.org/10.1098/rstb.2008.0242.

Oh, J. 2011. A consideration for the better preparedness against mega-disaster: Lessons from the 2011 Great Eastern Japan Earthquake and tsunami. Pukyong National University. http://www.kf.or.kr/file/kor_1/Panel_1_Jai-Ho_Oh_발표요약문.pdf (accessed October 10, 2011).

Polovina, J., E. Howell, D. Kobayashi, and M. Seki. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography* 49:469–483, http://dx.doi.org/10.1016/S0079-6611(01)00036-2.

Polovina, J., F. Chai, E. Howell, D. Kobayashi, L. Shi, and Y. Chao. 2008. Ecosystem dynamics at a productivity gradient: A study of the lower trophic dynamics around the northern atolls in the Hawaiian Archipelago. *Progress in Oceanography* 77:217–224, http://dx.doi.org/10.1016/j.pocean.2008.03.011.

Rios, L.M., P.R. Jones, C. Moore, and U.V. Narayan. 2010. Quantitation of persistent organic pollutants adsorbed on plastic debris from the North Pacific Gyre's "eastern garbage patch." *Journal of Environmental Monitoring* 12:2,226–2,236, http://dx.doi.org/10.1039/c0em00239a.

Ruiz, G.M., P.W. Fofonoff, J.T. Carlton, M.J. Wonham, and A.H. Hines. 2000. Invasion of coastal marine communities in North America: Apparent patterns, processes, and biases. *Annual Review of Ecology and Systematics* 31:481–531, http://dx.doi.org/10.1146/annurev.ecolsys.31.1.481.

Saito, H., A. Tsuda, and H. Kasai. 2002. Nutrient and plankton dynamics in the Oyashio region of the western subarctic Pacific Ocean. *Deep-Sea Research Part II* 49:5,463–5,486, http://dx.doi.org/10.1016/S0967-0645(02)00204-7.

Satheesh, S., and S.G. Wesley. 2009. Impact of December 26, 2004 tsunami on the hydrobiology of Kudankulam coast, Gulf of Mannar, India. *Environmental Monitoring and Assessment* 156:131–139, http://dx.doi.org/10.1007/s10661-008-0469-1.

Showstack, R. 2011. Oceanographer tracks marine debris from the Japan tsunami and other incidents. *Eos, Transactions American Geophysical Union* 92(37), 306, http://dx.doi.org/10.1029/2011EO370002.

Teuten, E.L., J.M. Saquing, D.R.U. Knappe, M.A. Barlaz, S. Jonsson, A. Björn, S.J. Rowland, R.C. Thompson, T.S. Galloway, R. Yamashita, and others. 2009. Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of The Royal Society B* 364:2,027–2,045, http://dx.doi.org/10.1098/rstb.2008.0284.

Thiel, M., and L. Gutow. 2005. The ecology of rafting in the marine environment: Part II. The rafting organisms and community. Pp. 279–418 in *Oceanography and Marine Biology: An Annual Review,* vol. 43. R.N. Gibson, R.J.A. Atkinson, and J.D.M. Gordon, eds, Taylor & Francis.

Ueno, D., S. Takahashi, H. Tanaka, A.N. Subramanian, G. Fillmann, H. Nakata, P.K.S. Lam, J. Zheng, M. Muchtar, K. Prudente, and others. 2003. Global pollution monitoring of PCBs and organochlorine pesticides using skipjack tuna as a bioindicator. *Archives of Environmental Contaminants Toxicology* 45:378–389, http://dx.doi.org/10.1007/s00244-002-0131-9.

Venrick, E.L., T.W. Backman, W.C. Bartram, C.J. Platt, M.S. Thornhill, and R.E. Yates. 1973. Man-made objects on the surface of the Central North Pacific Ocean. *Nature* 241:271, http://dx.doi.org/10.1038/241271a0.

Vives i Batlle, J. 2011. Impact of nuclear accidents on marine biota. *Integrated Environmental Assessment and Management* 7:365–367, http://dx.doi.org/10.1002/ieam.231.

von Westernhagen, H., M. Landolt, R. Kocan, G. Furstenberg, D. Janssen, and K. Kremling. 1987. Toxicity of sea-surface microlayer: Effects on herring and turbot embryos. *Marine Environmental Research* 23:273–290, http://dx.doi.org/10.1016/0141-1136(87)90022-5.

Watanabe, Y. 2009. Recruitment variability of small pelagic fish populations in the Kuroshio-Oyashio transition region of the Western North Pacific. *Journal of Northwest Atlantic Fisheries Science* 41:197–204, http://dx.doi.org/10.2960/J.v41.m635.

Williams, S., and J.E. Smith. 2007. A global review of the distribution, taxonomy, and impacts of introduced seaweeds. *Annual Review of Ecology, Evolution, and Systematics* 38:327–359, http://dx.doi.org/10.1146/annurev.ecolsys.38.091206.095543.

Yan, Z., and D. Tang. 2009. Changes in suspended sediments associated with 2004 Indian Ocean Tsunami. *Advances in Space Research* 43:89–95, http://dx.doi.org/10.1016/j.asr.2008.03.002.

Ye, S., and A.L. Andrady. 1991. Fouling of floating plastic debris under Biscayne Bay exposure conditions. *Marine Pollution Bulletin* 22(12):608–613, http://dx.doi.org/10.1016/0025-326X(91)90249-R.

Young, L.C., C. Vanderlip, D.C. Duffy, V. Afanasyev, and S.A. Shaffer. 2009. Bringing home the trash: Do colony-based differences in foraging distribution lead to increased plastic ingestion in Laysan Albatrosses? *PLoS One* 4(10):1–9, http://dx.doi.org/10.1371/journal.pone.0007623.

Zainuddin, M., H. Kiyofuji, K. Saitoh, and S. Saitoh. 2006. Using multi-sensor satellite remote sensing and catch data to detect ocean hot spots for albacore (*Thunnus alalunga*) in the northwestern North Pacific. *Deep-Sea Research Part II* 53:419-431, http://dx.doi.org/10.1016/j.dsr2.2006.01.007.