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Special Issue: *Transoceanic Dispersal of Marine Life from Japan to North America and the Hawaiian Islands as a Result of the Japanese Earthquake and Tsunami of 2011*

Co-Editors' Preface

Ocean rafting and marine debris: A broader vector menu requires a greater appetite for invasion biology research support

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Marine anthropogenic debris drifting along coastlines and across oceans with living species aboard (Kiessling et al. 2015; Rech et al. 2016; Carlton et al. 2017) now adds to the increasing list of human-mediated vectors transporting species across biogeographic barriers (Yeo et al. 2010; Williams et al. 2013; Grosholz et al. 2015; Fowler et al. 2016). This global bioflow may be further exacerbated by anthropogenic climate change, opening up new biogeographic regions previously inhospitable to warmer-water species (Doney et al. 2012; Bates et al. 2014; Canning-Clode and Carlton 2017). Climate change may also increase the frequency and magnitude of storm activity capable of washing the immense amounts of plastic material now poised on the edges of the world's coastlines into the sea (Carlton et al. 2017). In short, a combination of increasing vector diversity and changing climate sets the stage for a new era of invasions in the world's oceans.

The potential for colonization of North America and the Hawaiian Islands by species transported on Japanese tsunami marine debris (JTMD) is one of the most consistently posed questions since the first landfall in 2012 in Oregon of a huge fisheries dock torn away by the tsunami from the Port of Misawa on Honshu's Tōhoku coast (Carlton et al. 2018). While new populations of non-native species may take years to grow to the point of detection—a phenomenon known as invasion lag-time—we touch here upon a related challenge to addressing this question: that even as the number of species being transported increases, there is an ever-decreasing ability, as we argue below, to recognize alien species in the sea. This widening gap may delay and impair our understanding of changes to marine biodiversity and the resulting ecological, economic, evolutionary, and other impacts.

Wasson et al. (2000) noted that, "Detection of recent invasions of new regions by species from elsewhere is straightforward only for taxa for which there are accurate systematic descriptions and extensive and reliable historical records of distributions." They further argued that only a few marine groups (such as brachyuran decapods (crabs), gastropod mollusks (snails) and asteroid echinoderms (sea stars)) satisfy this formula. Among marine invertebrates (whether introduced or native) this thus leaves a staggering array of prominent—but often smaller-bodied and taxonomically-challenging—taxa all but unmonitored on coastlines around the world. Notably also under-reported are parasites, which often are similarly difficult to detect, cryptic, and likewise taxonomically challenging. As with free-living species, introductions of non-native parasites in marine ecosystems have led to major impacts on populations and communities (Blakeslee et al. 2013). When these smaller marine invertebrates are reported as novel introductions to a location or region, they are often one of only a few species being monitored in the entire class or phylum by the marine biological science community. Critically, all of these under-represented taxa are documented as being transported by a wide range of anthropogenic vectors (Table 1, taxa in boldface). Not surprisingly, the invertebrate taxa detected on JTMD mirror this pattern (Table 1).

In addition to invertebrates, algae are of course also transported globally, often attached to ships' hulls, rafting structures or as packing material for several vectors (Fowler et al. 2016; Hanyuda et al. 2017). Non-native algae can contribute substantially to the species richness of introduced communities, altering community structure. However, globally, almost 40% of algal species remain undescribed, further hindering the ability to accurately document species invasions (Guiry 2012).

While modern techniques of biodiversity assessment, such as genetic sequencing of individual specimens, targeted searches for individual species with eDNA, or metagenomic analyses of community samples, can assist in the identification and thus detection of species, the fundamental need for traditional morphological taxonomy (ideally combined with molecular approaches) remains largely unchanged, nearly 20 years after Wasson et al.'s (2000) assessment—and 65 years after Hedgpeth et al.'s (1953) call to arms. As Carlton et al. (2017) note, and as demonstrated by the contributions to this Special Issue, 80 systematists and other scientists from around the world were required to resolve only a portion of the fauna recovered from JTMD.

Detection of changes in marine biodiversity requires detailed and time-sensitive assessments across a broad suite of benthic communities (including rocky shores, soft-bottoms, salt marshes, and biofouling assemblages) and plankton and nektonic communities. All such surveys require sufficient funding not only for the appropriate levels of repeated field sampling (both spatially and temporally), but also for the recruitment of taxonomic specialists trained in both morphological and genetic techniques. The scientists who contributed to a knowledge of JTMD biodiversity worked mostly on a voluntary basis, a situation which would not be expected (nor even possible in the absence of equipment and supplies) of those doing broad spatial scale biodiversity sampling.

It is clear that the vast majority of taxonomic groups are bereft of widely-available taxonomic expertise and are thus typically under-reported as invasions (Table 1). New occurrences of introduced species in these and other groups on the Pacific coast of North America and in Hawaii may thus go undetected and, of course, this applies to any inter-regional species transfers on a world-wide basis. That these lesser known taxa have led to significant ecological, environmental, and economic impacts as invaders is well-known and long documented (Rilov and Crooks 2009), and yet the number of skilled taxonomic experts for aquatic taxa continues to wane in many global regions, with institutional support similarly disappearing even in those institutions (such as museums) dedicated to the study of taxonomy and biodiversity.

The answer then, to one of the most common questions relative to JTMD—*will new invasions by exotic species occur, or have they occurred already?*—is yes, perhaps, but how many of them will we be able to detect? An enduring assumption among the public and press, as well as in the political world, is that "marine biologists" are in a position to answer this question, based upon the presumption that the scientific community has their "finger on the pulse" of changes in marine biodiversity, especially in accessible intertidal and nearshore waters. But, save for the invasion of larger-bodied and relatively abundant species, such knowledge for most groups would require an infusion of dedicated, and stable, funding of field surveys (and the supporting laboratory work), as well as the non-optional funding to greatly increase the number of experts trained and qualified to identify species that do not fall into the iconic, charismatic, commercially, or recreationally important categories. Of the 80 scientists who contributed to the JTMD program, only five live and work in North America and Hawaii (where the JTMD arrived) and are employed full-time as professional systematic zoologists.

Marine dispersal ecology is an increasingly fluid field of research. While dispersal of life in the sea has long been viewed as an overwhelmingly natural process, striking shifts in the diversity and efficacy of anthropogenic vectors in modern time have altered the distribution of many thousands of marine species. The stage appears to be set for this phenomenon to continue and grow. We strongly echo Pysek et al. (2013), who have eloquently argued—relative to terrestrial

Table 1. Examples of marine invertebrates and fish transported by selected anthropogenic vectors.

Marine Faunal Taxa		**Vectors**				
		Vessels:			**Fisheries:**	**Rafting:**
Boldface: Examples of groups that are **globally under-reported as invasions** (Wasson et al. 2000; Carlton 2003, 2009; Carlton and Eldredge 2009, 2015; Mead et al. 2011a, 2011b)		**Ballast water and sediments**	**Sea chests**	**Semi-submersible platforms**	**Seaweed as baitworm dunnage**	**Marine debris**
		Gollasch et al. 2002; NRC 2011	Coutts and Dodgshun 2007; Frey et al. 2014	Wanless et al. 2010; Hopkins and Forrest 2010; Yeo et al. 2010	Miller 1969; Haska et al. 2012; Cohen 2012; Fowler et al. 2016	Carlton et al. 2017
Group	**Common Name**					
PORIFERA	**sponges**	(1)	x	x	x	x
CNIDARIA						
Hydrozoa	**hydroids**	x	x	x	x	x
Anthozoa: Actiniaria	**sea anemones**	x	x	x	x	x
PLATYHELMINTHES	**flatworms**	x	x	x	x	x
NEMERTEA	**ribbon worms**	x	x	x	x	x
NEMATODA	**round worms**	x	x	x	x	x
KAMPTOZOA	**nodding heads**	*	x	x		x
ANNELIDA						
Sipuncula	**peanut worms**	*	x	x		x
Oligochaeta	**oligochaete worms**	x	x	x	x	x
Polychaeta	**polychaete worms**	x	x	x	x	x
ARTHROPODA						
Ostracoda	**ostracods**	x	*	x	x	x
Copepoda	**copepods**	x	x	x	x	x
Cirripedia	**barnacles**	x	x	x	x	x
Mysidacea	**opossum shrimp**	x	x		x	
Isopoda	**isopods**	x	x	x	x	x
Tanaidacea	**tanaids**	x	x	x	x	x
Amphipoda	**amphipods**	x	x	x	x	x
Decapoda: Brachyura	crabs	x	x	x	x	x
Decapoda: Caridea	**shrimp**	x	x	x		
Pycnogonida	**sea spiders**	*	x	x		x
Arachnida	**mites**	x	x	x	x	x
Insecta	**insects**	x	x	x	x	x
MOLLUSCA						
Gastropoda	snails	x	x	x	x	x
Bivalvia	**clams, mussels, oysters, scallops**	x	x	x	x	x
BRYOZOA	**moss animals**	x	x	x	x	x
ECHINODERMATA						
Asteroidea	sea stars	x	x	x	x	x
Ophiuroidea	**brittle stars**	x		x		x
CHORDATA						
Ascidiacea	**sea squirts**	x	x	x		x
Pisces	fish	x	x	x		x

(1) Kipp et al. (2010) and Briski et al. (2011) report freshwater sponges in ballast water and sediments.
* Taxa relatively difficult to detect due to their small size, or to their presence as larvae, and thus likely overlooked.

plant invasions—that taxonomic resources are indispensable ingredients for the effective detection and management of biological invasions, and that the time is now here for a “resurgence and reinvestment” in 21st century taxonomy. We believe their arguments apply equally and fully to the marine environment, in an ocean now abounding with the human-mediated means to instantaneously move almost any species around the world in a matter of days if not hours.

Under-reporting of introduced species, due to a dearth of surveys and lack of taxonomic expertise, especially relative to under-studied groups, undermines key aspects of the management of species and ecosystems impacted by non-natives, including early detection of introduced species and rapid response. Without support for these fundamental biodiversity assessment resources, our ability to document new invasions will continue to decline, and we may thus be unable to describe how marine communities are responding to such invasions and what the consequences will be to the environment and human welfare, until economic, social, or health impacts become politically problematic.

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References

Bates AE, Pecl GT, Frusher S, Hobday AJ, Wernberg T, Smale DA, Sunday JM, Hill NA, Dulvy NK, Colwell RK, Holbrook NJ, Fulton EA, Slawinski D, Feng M, Edgar GJ, Radford BT, Thompson PA, Watson RA (2014) Defining and observing stages of climate-mediated range shifts in marine systems. *Global Environmental Change* 26: 27–38, https://doi.org/10.1016/j.gloenvcha.2014.03.009

Blakeslee AMH, Fowler AE, Keogh CL (2013) Marine invasions and parasite escape: updates and new perspectives. *Advances in Marine Biology* 66: 87–169, https://doi.org/10.1016/B978-0-12-408096-6.00002-X

Briski E, Bailey SA, MacIsaac HJ (2011) Invertebrates and their dormant eggs transported in ballast sediments of ships arriving to the Canadian coasts and the Laurentian Great Lakes. *Limnology and Oceanography* 56: 1929–1939, https://doi.org/10.4319/lo.2011.56.5.1929

Canning-Clode J, Carlton JT (2017) Refining and expanding global climate change scenarios in the sea: poleward creep complexities, range termini, and setbacks and surges. *Diversity and Distributions* 23: 463–473, https://doi.org/10.1111/ddi.12551

Carlton JT (2003) Community assembly and historical biogeography in the North Atlantic Ocean: the potential role of human-mediated dispersal vectors. *Hydrobiologia* 503: 1–8, https://doi.org/10.1023/B:HYDR.0000008479.90581.e1

Carlton JT (2009) Deep invasion ecology and the assembly of communities in historical time. In: Rilov R, Crooks JA (eds), Biological Invasions in Marine Ecosystems. Springer-Verlag, pp 13–56, https://doi.org/10.1007/978-3-540-79236-9_2

Carlton JT, Chapman JW, Geller JB, Miller JA, Ruiz GM, Carlton DA, McCuller MI, Treneman NC, Steves BP (2017) Tsunami-driven rafting: Transoceanic species dispersal and implications for marine biogeography. *Science* 357: 1402–1406, https://doi.org/10.1126/science.aao1498

Carlton JT, Chapman JW, Geller JB, Miller JA, Ruiz GM, Carlton DA, McCuller MI, Treneman NC, Steves BP, Breitenstein RA, Lewis R, Bilderback D, Bilderback D, Haga T, Harris LH (2018) Ecological and biological studies of ocean rafting: Japanese tsunami marine debris in North America and the Hawaiian Islands. *Aquatic Invasions* 13: 1–9, https://doi.org/10.3391/ai.2018.13.1.01

Carlton JT, Eldredge LG (2009) Marine bioinvasions of Hawai'i. The introduced and cryptogenic marine and estuarine animals and plants of the Hawaiian Archipelago. Bishop Museum Bulletins in Cultural and Environmental Studies 4, Bishop Museum Press, Honolulu, 202 pp

Carlton JT, Eldredge LG (2015) Update and Revision of The Marine Bioinvasions of Hawai'i: The Introduced and Cryptogenic Marine and Estuarine Animals and Plants of the Hawaiian Archipelago. In: Evenhuis NL, Carlton JT (eds), Lucius G. Eldredge III Memorial Volume: Tribute to a Polymath. Bishop Museum Bulletin Zoology 9, pp 25–47

Cohen AN (2012) Aquatic invasive species vector risk assessments: Live saltwater bait and the introduction of non-native species into California. Final report for California Ocean Science Trust, 58 pp. http://www.opc.ca.gov/webmaster/ftp/project_pages/AIS/AIS_LiveSeafood.pdf

Coutts ADM, Dodgshun TJ (2007) The nature and extent of organisms in vessel sea-chests: a protected mechanism for marine bioinvasions. *Marine Pollution Bulletin* 54: 875–886, https://doi.org/10.1016/j.marpolbul.2007.03.011

Doney SC, Ruckelshaus M, Duffy JE, Barry JP, Chan F, English CA, Galindo HM, Grebmeier JM, Hollowed AB, Knowlton N, Polovina J, Rabalais NN, Sydeman WJ, Talley LD (2012) Climate change impacts on marine ecosystems. *Annual Review of Marine Science* 4: 11–37, https://doi.org/10.1146/annurev-marine-041911-111611

Fowler AE, Blakeslee AMH, Canning-Clode J, Repetto MF, Phillip AM, Carlton JT, Moser FC, Ruiz GM, Miller AW (2016) Opening Pandora's bait box: a potent vector for biological invasions of marine species. *Diversity and Distributions* 22: 30–42, https://doi.org/10.1111/ddi.12376

Frey MA, Simard N, Robichaud DD, Martin JL, Therriault TW (2014) Fouling around: vessel sea-chests as a vector for the introduction and spread of aquatic invasive species. *Management of Biological Invasions* 5: 21–30, https://doi.org/10.3391/mbi.2014.5.1.02

Gollasch S, MacDonald E, Belson S, Botnen H, Christensen JT, Hamer JP, Houvenaghel G, Jelmert A, Lucas I, Masson D, McCollin T, Olenin S, Persson A, Wallentinus I, Wetsteyn LPMJ, Wittling T (2002) Life in ballast tanks. In: Leppäkoski E, Gollasch S, Olenin S (eds), Invasive aquatic species of Europe distribution, impact and management. Kluwer Academic Publishers, pp 217–231, https://doi.org/10.1007/978-94-015-9956-6_23

Grosholz ED, Crafton RE, Fontana RE, Pasari JR, Williams SL, Zabin CJ (2015) Aquaculture as a vector for marine invasions in California. *Biological Invasions* 17: 1471–1484, https://doi.org/10.1007/s10530-014-0808-9

Guiry MD (2012) How many species of algae are there? *Journal of Phycology* 48: 1057–1063, https://doi.org/10.1111/j.1529-8817.2012.01222.x

Hanyuda T, Hansen GI, Kawai H (2017) Genetic identification of macroalgal species on Japanese tsunami marine debris and genetic comparisons with their wild populations. *Marine Pollution Bulletin*, https://doi.org/10.1016/j.marpolbul.2017.06.053

Haska CL, Yarish C, Kraemer G, Blaschik N, Whitlatch R, Zhang H, Lin S (2012) Bait worm packaging as a potential vector of invasive species. *Biological Invasions* 14: 481–493, https://doi.org/10.1007/s10530-011-0091-y

Hedgpeth JW, Menzies RJ, Hand CH, Burkenroad MD (1953) On certain problems of taxonomists. *Science* 117: 17–18, https://doi.org/10.1126/science.117.3027.17-a

Hopkins GA, Forrest BM (2010) Challenges associated with pre-border management of biofouling on oil rigs. *Marine Pollution Bulletin* 60: 1924–1929, https://doi.org/10.1016/j.marpolbul.2010.07.015

Kiessling T, Gutow L, Thiel M (2015) Chapter 6, Marine litter as habitat and dispersal vector. In: Bergmann M, Gutow L, Klages M (eds), Marine Anthropogenic Litter. Springer, pp 141–181, https://doi.org/10.1007/978-3-319-16510-3_6

Kipp R, Bailey SA, MacIsaac HJ, Ricciardi A (2010) Transoceanic ships as vectors for nonindigenous freshwater bryozoans. *Diversity and Distributions* 16: 77–83, https://doi.org/10.1111/j.1472-4642.2009.00629.x

Mead A, Carlton JT, Griffiths CL, Rius M (2011a) Revealing the scale of marine bioinvasions in developing regions: a South African re-assessment. *Biological Invasions* 13: 1991–2008, https://doi.org/10.1007/s10530-011-0016-9

Mead A, Carlton JT, Griffiths CL, Rius M (2011b) Introduced and cryptogenic marine and estuarine species of South Africa. *Journal of Natural History* 45: 2463–2524, https://doi.org/10.1080/00222933.2011.595836

Miller RC (1969) *Ascophyllum nodosum*: a source of exotic invertebrates introduced into west coast near-shore marine waters. *Veliger* 12: 230–231

National Research Council (NRC) (2011) Assessing the relationship between propagule pressure and invasion risk in ballast water. Committee on Assessing Numeric Limits for Living Organisms in Ballast Water, National Research Council. The National Academies Press, Washington, D.C., 144 pp

Pysek P, Hulme PE, Meyerson LA, Smith GF, Boatwright JS, Crouch NR, Figueiredo E, Foxcroft LC, Jarosik V, Richardson DM, Suda J, Wilson JRU (2013) Hitting the right taxonomic challenges for, and of, plant invasions. *AoB Plants* 5: plt042, https://doi.org/10.1093/aobpla/plt042

Rech S, Borrell Y, Garcia-Vasquez E (2016) Marine litter as a vector for non-native species: what we need to know. *Marine Pollution Bulletin* 113: 40–43, https://doi.org/10.1016/j.marpolbul.2016.08.032

Rilov G, Crooks JA (2009) Biological Invasions in Marine Ecosystems. Springer-Verlag, pp 241–326, https://doi.org/10.1007/978-3-540-79236-9

Wanless RM, Scott S, Sauer WHH, Andrew TG, Glass JP, Godfrey B, Griffiths C, Yeld E (2010) Semi-submersible rigs: a vector transporting entire marine communities around the world. *Biological Invasions* 12: 2573–2583, https://doi.org/10.1007/s10530-009-9666-2

Wasson K, Von Holle B, Toft J, Ruiz G (2000) Detecting invasions of marine organisms: kamptozoan case histories. *Biological Invasions* 2: 59–74, https://doi.org/10.1023/A:1010049907067

Williams SL, Davidson IC, Pasari JR, Ashton GV, Carlton JTC, Crafton RE, Fontana RE, Grosholz ED, Miller AW, Ruiz GM, Zabin CJ (2013) Managing multiple vectors for marine invasions in an increasingly connected world. *Bioscience* 63: 952–966, https://doi.org/10.1525/bio.2013.63.12.8

Yeo DCJ, Ahyong ST, Lodge DM, Ng PKL, Naruse T, Lane DJW (2010) Semisubmersible oil platforms: understudied and potentially major vectors of biofouling-mediated invasions. *Biofouling* 26: 179–186, https://doi.org/10.1080/08927010903402438