

1 **Relationship of diversity and habitat area in North Pacific plastic-**
2 **associated rafting communities**

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11 ***Abstract***

12 Plastic and other anthropogenic debris (e.g., rubber, tar) augment natural floating
13 substrates (e.g., algal rafts, pumice) in the open ocean, allowing “islands” of substrate-associated
14 organisms to persist in an otherwise unsuitable habitat. We examined a total of 242 debris
15 objects collected in the eastern Pacific in 2009 and 2011 (32-39°N, 130-142°W) and the western
16 Pacific in 2012 (19-41°N, 143-156°E). Here, we ask: (a) What taxa are associated with plastic
17 rafts in the North Pacific? and (b) Does the number of taxa associated with plastic debris vary
18 with the size of the debris “island?” We documented 95 rafting taxa from 11 phyla. We
19 identified several potentially invasive plastic-associated rafting taxa, including the coral
20 pathogen *Halofolliculina* spp. In concordance with classic species-area curves, the number of
21 rafting taxa was positively correlated with the size of the raft. Our findings suggest that diversity
22 patterns on plastic debris are compatible with the concept of island biogeography.

23 ***Introduction***

24 Naturally occurring floating objects in the pelagic environment have long played host to a
25 suite of specialized species (Thiel & Gutow 2005a). These substrates, such as floating algae,
26 pumice, and wood, provide transport and habitat for benthic organisms (Donlan and Nelson
27 2003; Thiel and Gutow 2005b; Bryan et al. 2012). In recent decades, natural rafts have been
28 augmented by anthropogenic debris comprised primarily of non-biodegradable plastic polymers
29 such as hard thermoplastic, foam, synthetic rubber, and fiberglass (Derraik 2002; Barnes et al.
30 2009).

31 Plastic debris was first detected in the open ocean in the early 1970s (Carpenter and
32 Smith 1972; Venrick et al. 1973; Wong et al. 1974) and has now been observed all over the
33 world (Thiel & Gutow 2005a). Plastic enters the marine environment through improper disposal
34 (e.g., litter) or accidental loss (e.g., fishing gear; U.S. Environmental Protection Agency 2011).
35 Debris from land-based sources is most common near highly populated areas, while debris from
36 marine sources is most common on remote shores (Hammer et al. 2012). However, as debris is
37 exposed to UV light and physical weathering, it fragments into small pieces, termed
38 microplastics, that are frequently less than 5 mm in diameter (Andrady 2011; Hidalgo-Ruz et al.
39 2012). Microplastics now comprise the vast numerical majority of debris in the ocean (Goldstein
40 et al. 2013) though larger objects that can support a more extensive rafting community are far
41 from uncommon (Titmus and Hyrenbach 2011, Ryan 2013).

42 The composition of the rafting assemblage depends on the type of object, its stability, and
43 the supply of propagules (Thiel and Gutow 2005b). In general, artificial substrates do not host
44 the same communities as natural substrates (Tyrrell and Byers 2007; Pister 2009; but see Bravo
45 et al. 2011). In the case of floating objects, biotic rafts (e.g., wood, detached kelp) do not float

46 for as long as abiotic rafts (e.g., plastic, tar, pumice), but do provide a food source for rafting
47 organisms, and may therefore may be more successful at transporting a variety of species
48 (Donlan and Nelson 2003; Thiel and Gutow 2005b). Items with a complex surface (e.g., pumice,
49 macroalgae holdfasts) may provide better habitat than items with a smooth surface (e.g., plastic
50 bottles; Thiel and Gutow 2005b). The rotational stability of the rafting object may also affect the
51 diversity of the attached assemblage – pieces with fewer changes of orientation have greater
52 species richness and cover than less stable pieces (Bravo et al. 2011; Bryan et al. 2012). Fouling
53 also increases the specific density of the raft, which may cause sinking in the water column and
54 potentially a subsequent rise to the surface if fouling organisms die or are removed by predators
55 (Ye and Andrady 1991; Moret-Ferguson et al. 2010), though fouling can also help maintain the
56 positive buoyancy of porous rafts (e.g., pumice, foam) by reducing gas permeability (Bryan et al.
57 2012). Lastly, the physical environment around the raft, such as distance from shore or water
58 temperature, may be more significant to rafting species composition than characteristics of the
59 raft itself (Clarkin et al. 2012). For example, rafts that were colonized in coastal waters may have
60 different species composition than rafts colonized at sea (Astudillo et al. 2009), and the diversity
61 of the rafting community may be enhanced by encounters with larval sources such as islands,
62 reefs, and other shallow-water habitats (Bryan et al. 2012).

63 Diversity patterns in open-ocean rafting assemblages, particularly plastic-associated
64 assemblages, are largely unexplored. In many ecosystems, diversity is predicted by the species-
65 area curve, in which the number of species increases as a function of available surface area,
66 though the shape of this curve has been a matter of some debate (He and Legendre 1996).
67 Species-area curves can be explained by the concept of island biogeography, which predicts that
68 species diversity is a balance between arrival of species through migration and the loss through

69 extinction, both processes that vary with available habitat area (MacArthur and Wilson 1963).
70 While species-area relationships are one of the most widely observed patterns in ecology, there
71 are exceptions, such as the “small-island effect,” in which the areas of the ecosystems observed
72 are all too small for a diversity pattern to be detected (Lomolino 2000). It is unknown whether
73 plastic-associated rafting assemblages follow the species-area pattern, particularly since
74 organisms with certain life history traits, such as suspension feeding, are more likely to be
75 successful rafters, especially on abiotic substrata such as plastic (Thiel and Hays 2006).

76 The light weight and durability of plastic make it a vector for the transport of
77 nonindigenous species. For example, a piece of flotsam with traces of tropical biota, including
78 self-fertilizing corals, was recently discovered in the Netherlands (Hoeksema et al. 2012), and
79 Southern Ocean bryozoans in reproductive condition were found on a beached packing band in
80 Antarctica (Barnes and Fraser 2003). Benthic organisms such as bryozoans, barnacles, and
81 hydroids are commonly found on plastic debris (Aliani and Molcard 2003; Barnes and Milner
82 2005; Farrapeira 2011). The particular vulnerability of island ecosystems to invasions and the
83 ubiquity of plastic debris on the mid-Pacific islands makes lateral transport of fouling species a
84 matter of particular concern in the North Pacific (McDermid and McMullen 2004). Recently, a
85 non-native hydroid and two ascidians were recorded from debris collected in the Northwest
86 Hawaiian Islands (Godwin et al. 2008). However, most studies have examined beached material,
87 not *in situ* debris (Winston et al. 1997; Barnes 2002; Barnes and Fraser 2003; Barnes and Milner
88 2005; Hoeksema et al. 2012; but see Astudillo et al. 2009).

89 Even when debris does not carry organisms to distant shorelines, debris can provide
90 abundant habitat to fouling organisms. In coastal areas, abundance of floating macroalgae varies
91 between 1 and 1000 items km⁻², occasionally even exceeding values of 10,000 items km⁻² (Thiel

92 and Gutow 2005a). High densities of abiotic substrates can also occur in the open ocean – one
93 eruption in Tonga was estimated to release over 2.5×10^{12} individual pumice clasts, more than
94 50% of which were inhabited by rafting organisms (Bryan et al. 2012). Floating microplastic
95 debris in the subtropical gyres can also reach high densities, such as a median of 425,000 items
96 km^{-3} in the North Pacific Subtropical Gyre (Goldstein et al. 2012) and a mean of 20,328 items
97 km^{-2} in the North Atlantic Subtropical Gyre (Law et al. 2010). This increase in habitat has the
98 potential to expand populations of open-ocean rafting species, such as gooseneck barnacles
99 (Whitehead et al. 2011) and oceanic insects (Goldstein et al. 2012; Majer et al. 2012).

100 In this study, we asked: (a) What taxa are associated with drifting plastic in the North
101 Pacific? (b) Does the number of taxa associated with plastic debris vary with the size of the
102 debris “island?”

103

104 ***Methods***

105 Samples were collected on three cruises, the 2009 Scripps Environmental Accumulation
106 of Plastics Expedition (SEAPLEX), the 2011 Algalita Eastern North Pacific Gyre Expedition and
107 2012 Western North Pacific Gyre Expedition (Fig. 1).

108 For the 2009 samples, floating debris items were opportunistically collected by dip net
109 (39 cm length x 33.5 cm width, mesh 1 mm). If possible, the entire piece of debris with attached
110 fauna was preserved in either 5% Formalin buffered with sodium borate or 95% ethanol. An
111 attempt was made to preserve portions of most samples in both preservatives to allow for both
112 morphological and molecular studies. When the item was too large to be preserved, the item was
113 either subsampled (e.g., portions of a tarp were cut and preserved) or the fauna were removed
114 and preserved separately (e.g., in the case of a large fishing buoy). A subset of plastics collected

115 using a standard manta net (0.86 x 0.2 m) with 333- μ m mesh (Brown and Cheng 1981), towed
116 for 15 minutes at 0.7-1 m s⁻¹ were also included in this study. For smaller manta-net-collected
117 debris particles, 50% aliquots of the net-collected samples were analyzed. Since splitting samples
118 causes the less abundant larger debris items to be undersampled, all manta-net-collected objects
119 with a diameter of greater than 2 cm were included in this study. For this reason, we found it
120 practical to use the 2 cm cutoff to divide “fragments” from larger objects.

121 On the 2011 and 2012 expeditions, debris items were collected by dipnet during timed
122 debris observation periods or opportunistically during other daylight sightings. Debris items were
123 inspected for attached organisms immediately, and then taken to shipboard laboratory for
124 microscope inspection, photography, and preservation. If possible, the entire piece of debris with
125 attached fauna was preserved in 5% Formalin as on the 2009 cruise. Where not possible,
126 organisms were removed and preserved separately. Three floating masses of nets, rope, and
127 entangled debris were sampled differently. In 2011, the net mass was examined by divers in the
128 water, who noted associated fishes, collected fouling organisms opportunistically, and
129 subsampled the materials for inspection on board. In 2012 both net masses were inspected in the
130 water first, and then hauled on board and dissected on deck for a more thorough collection of
131 fouling organisms.

132 In the laboratory, objects from the 2009 expedition were examined for rafting fauna
133 under a Wild M-5 dissecting microscope. The preservative was also filtered through 150- μ m
134 Nitex mesh to retain non-attached biota. During the 2011 and 2012 expeditions, organisms and
135 small debris were inspected and photographed on board using a Dino-Lite Premiere Digital
136 Microscope. All objects were photographed with *in situ* size references. Two-dimensional
137 surface area was digitally measured using the NIH ImageJ software (Rasband 2012) calibrated

138 against manual measurements. Because of the flattened shape of most debris objects, we
139 approximated total surface area by multiplying two-dimensional surface area by a factor of two.
140 It should be noted that this approach substantially underestimates the total surface area of
141 complex structures such as rope clumps and net balls.

142 Later identification of preserved specimens in the laboratory was made using dissection
143 or compound microscopes. All fauna were identified to the lowest possible taxonomic level.
144 When objects with different taxonomic resolutions were compared, taxa were collated to
145 comparable levels. For example, *Lepas pacifica*, *L. anatifera*, and *Lepas* spp. were counted as
146 one taxon. To determine whether taxa had previously been documented as rafting, we first
147 consulted the comprehensive lists of rafting taxa given in Thiel & Gutow (2005b). If a given taxa
148 was not listed in Thiel & Gutow (2005b), we conducted a literature search to determine if we
149 could find other documentation of rafting in the taxa. If we could not find such documentation,
150 the taxa were listed as “not previously documented as rafting.” A complete list of debris
151 locations and associated taxa is given in Supplemental Table 1. We determined the feeding type
152 of each taxon from our own biological knowledge and from reference to the literature as
153 necessary. When the feeding ecology of a specific taxon was unknown, we assigned it to the
154 most probable feeding type. For example, an unidentified hydroid was classified as a
155 “suspension feeder.”

156 Statistics and figures were generated with the R statistical environment, version R-2.13.1
157 (R Development Core Team 2012). Debris object areas were log-transformed for ease of display.
158 We used the chi-square test to test if rafting assemblage traits (e.g., phyla composition, feeding
159 type) varied between cruises and years. We used Kendall’s tau rank correlation coefficient to
160 measure the strength of dependence between debris size and number of taxa. For one analysis,

161 both taxa and debris area were linearized using log-transformations so that the relationship could
162 be more easily visualized, and analyzed using linear regression (Lomolino 2000).

163

164 **Results**

165 We examined a total of 242 debris objects and identified 95 associated rafting taxa (Table
166 1). The debris comprised 66% rigid plastic fragments less than 2 cm in diameter, 21% rigid
167 plastic fragments or objects ranging from 2 to 100 cm in diameter, 7% rope clumps, 3% flexible
168 substrates (e.g., tarps), and 3% expanded foam (e.g., “Styrofoam”). Debris substrate area ranged
169 from $2.54 \times 10^{-7} \text{ m}^2$ to 15 m^2 , with a median of $1.18 \times 10^{-4} \text{ m}^2$.

170 Representatives of 11 phyla were found, with the most abundant phylum being the
171 Arthropoda, followed by Mollusca and Cnidaria (Fig 3a). The majority of these taxa were
172 suspension feeders, though omnivores, grazers, and predators were also well represented (Fig
173 3b). Slightly more taxa were mobile than were sessile (Fig 3c). Of all 95 identified taxa, 25
174 (26%) had not been previously found to occur in rafting assemblages (Fig 3d, Table 1). No
175 differences in the composition of phyla, feeding type, and mobile/sessile taxa were found
176 between cruise years/locations (Chi-square test, $P > 0.5$ for all tests).

177 We found a significant positive correlation between the size of the debris object and the
178 number of taxa found on that object (Fig 4a, Kendall’s tau, $\tau = 0.555$, $N = 242$, $P < 0.001$). This
179 correlation remained significant when the data were linearized through log transformation (Fig
180 4b, linear regression, $r^2 = 0.169$, $F_{1,66} = 48.69$, $P < 0.001$), as well as when the four largest items
181 were removed (linear regression, $r^2 = 0.086$, $F_{1,66} = 22.45$, $P < 0.001$). When cruises were examined
182 separately (Fig S1), there was a significant positive correlation between debris size and taxon
183 richness in 2009 (Kendall’s tau, $\tau = 0.561$, $N = 208$, $P < 0.001$) and 2011 (Kendall’s tau, $\tau = 0.650$,

184 $N=13, P=0.003$), but not in 2012 (Kendall's tau, $\tau=0.062, N=21, P=0.710$). We did not find a
185 relationship between distance offshore and number of taxa.

186 The eight most taxon-rich phyla also exhibited significant positive relationships between
187 object size and number of taxa (Fig S2, Kendall's tau $P<0.01$ for all phyla). However, for the
188 phyla that have few taxa (e.g., 1-3 taxa), these relationships are sensitive towards incidentally
189 occurring individuals.

190 We noted a shallow parabolic shape, in both our overall taxa-area semi-log curve and for
191 some of the phylum-specific curves, such as Arthropoda and Bryozoa. Higher numbers of taxa
192 were found on medium-sized objects (approximately $1 \times 10^{-2} \text{ m}^2$) as compared to slightly larger
193 objects (approximately 1 m^2), though the largest objects (approximately 10 m^2) retained the
194 overall highest numbers of taxa.

195

196 ***Discussion***

197 Composition of rafting assemblage

198 We found a diverse and widespread rafting assemblage inhabiting North Pacific plastic
199 debris. The majority of taxa were known members of the rafting assemblage such as *Lepas* spp.
200 barnacles and membraniporid bryozoans, but we documented 25 taxa that had not been
201 previously found in rafting assemblages. Many of the previously undocumented taxa were from
202 groups that are known to be prolific and successful rafters, such as the bryozoans, sponges, and
203 peracarid crustaceans (Barnes 2002; Thiel and Gutow 2005b). We were surprised to find a small
204 number of boring organisms rafting on pelagic plastic debris composed of foamed polystyrene.
205 These included the bivalve *Zirfaea*, the shipworm *Teredo*, and a sphaeromatid isopod. While
206 boring organisms are known to colonize rafts of biotic origin, such as wood and algae, they are

207 relatively rare on plastic debris (Thiel and Gutow 2005b; Thiel and Haye 2006), although
208 sphaeromatid isopods are known to burrow in polystyrene floats in coastal ecosystems (Davidson
209 2012).

210 Another organism of particular interest was the folliculinid ciliate (*Halofolliculina* spp.),
211 found in abundance on some western Pacific plastic debris. These ciliates are pathogens that
212 cause skeletal eroding band (SEB) disease in corals (Rodriguez et al. 2009). Though originally
213 thought to be limited to the Indian Ocean and South Pacific, SEB disease was discovered in
214 Caribbean corals in 2004 (Croquer et al. 2006) and in Hawaiian corals in 2010 (Palmer and
215 Gates 2010). The mechanism behind the spread of SEB are not known (Croquer et al. 2006), but
216 since the Hawaiian Islands are highly impacted by plastic debris collected by the North Pacific
217 subtropical convergence zone (Dameron et al. 2007), it is possible that debris facilitated the
218 dispersal of *Halofolliculina* to this area. Like many rafting substrates, plastic debris has the
219 potential to disperse non-ciliate pathogens, such as viruses, but the role of debris as a disease
220 fomite has been little studied (Maso et al. 2003, Pham et al. 2012).

221

222 Origin of rafting organisms

223 Many of the rafting taxa found are known invaders, but could have come either from their
224 native range or from an area in which they are already established as a non-native species. These
225 include the acorn barnacle *Megabalanus rosa*, native to Japan but an invasive species in
226 Australia; and the mussel *Mytilus galloprovincialis* and acorn barnacle *Amphibalanus amphitrite*,
227 which are invasive to the eastern Pacific (Fofonoff et al. 2012). Other taxa may have settled onto
228 debris in coastal areas and been transported offshore (Astudillo et al. 2009), such as the bryozoan
229 *Victorella* spp., which primarily occurs in estuarine waters (Carter et al. 2010).

230 Because most of the fauna present were either known members of the north Pacific
231 rafting assemblage or widely distributed taxa, the source of the debris objects could not be
232 determined from the associated assemblage. We know of no other reliable way to age or source
233 plastic debris (though see the general analysis of net type in Jacobsen et al. 2010). Even debris
234 with some identifying markings or text in a particular language cannot always be attributed to a
235 country of origin due to the extent of international trade and the variety of household items used
236 on ships.

237 The transport of invasive species on debris originating during the March 11th, 2011
238 Tohoku Earthquake and subsequent tsunami event has received much attention recently,
239 especially regarding objects such as docks that harbor entire communities of coastal organisms
240 (Choong and Calder 2013; Gewin 2013). It is possible that some debris collected on the 2011
241 and 2012 expeditions originated from the Japan tsunami. However, we believe this is unlikely,
242 since both expeditions occurred outside of the locations where high tsunami debris
243 concentrations were predicted to occur at the time of the expedition (Lebreton and Borrero
244 2013).

245

246 Relationship between number of taxa and debris size

247 We found a greater number of taxa on larger debris items than on smaller items. A
248 positive relationship between object size and taxa number has also been observed in algal rafts
249 (Ingólfsson 1995; Hobday 2000; Clarkin et al. 2012), fish aggregation devices (Nelson 2003),
250 and pumice (Bryan et al. 2012). The greater number of taxa on larger objects could be a
251 stochastic effect. If individuals are randomly distributed over all floating objects available, then
252 larger objects would receive more species. However, this relationship may also be driven by both

253 physical and biological factors. Physically, larger objects are more likely to remain buoyant,
254 even after developing a substantial rafting assemblage (Thiel and Gutow 2005a). Smaller objects
255 with a substantial rafting assemblage may have become negatively buoyant, and were therefore
256 not sampled by this study or by other studies focusing on material at the sea surface. In addition,
257 some objects were likely to have entered the water without attached biota (e.g., a toothbrush),
258 while some objects were likely to have had some attached biota at the time they were lost (e.g.,
259 an eel trap). Larger items were primarily associated with fishing activities, and may be more
260 likely to have a higher number of taxa due to previous attachments.

261 Biological interactions, as predicted by island biogeography, may also be an important
262 driver of the positive species-area relationship on pelagic plastic debris. As on islands, the rate of
263 migration to large pieces of plastic debris may exceed the rate of extinction (Simberloff 1976).
264 Higher rates of migration to larger objects could be driven by larval settlement. For example, due
265 to their greater surface area, larger objects may be more likely to give off the appropriate cues for
266 larval settlement (Rodriguez et al. 1993). Larger objects may also be easier for fishes to detect
267 through visual and auditory cues (Dempster and Kingford 2003). Furthermore, they are more
268 stable at the sea surface, which is an important driver of diversity (Bravo et al. 2011; Bryan et al.
269 2012). Large items without spatial stability may contain low diversity, such as a meter-long
270 cylindrical polystyrene buoy that “rolled” along the sea surface (H.S.C. *pers. obs.*). Lastly,
271 successional stage may influence diversity. A study in the western Pacific found that diversity
272 was highest during early stages of succession, and then reduced by *Lepas* dominance (Tsikhon-
273 Lukanina et al. 2001). The authors suggested that diversity may increase once more at later
274 successional stages, which they define as being dominated by bivalves. However, floating debris
275 in their study never reached this stage, perhaps due to lack of physical stability or limited larval

276 supply. A study on algal rafts suggested that the separation and exchange of rafting materials
277 may affect the successional progression, which may also apply to some marine debris (e.g. rope
278 and net masses) but may not apply to solid plastic objects which are less likely to coalesce
279 (Clarkin et al. 2012).

280 We have two potential explanations for the shallow parabolic shape of some the taxa-area
281 semi-log curves presented here: 1) it could be an artifact of different sampling methodologies for
282 medium and large objects; 2) higher predator abundance on large objects suppresses prey
283 diversity. We cannot rule out the parabola as a sampling artifact, because medium objects (e.g.,
284 plastic fragments) were preserved without subsampling, while large objects (e.g., buoys) had to
285 be subsampled at sea. The difference in preservation strategy could have caused inconspicuous
286 taxa on large objects to be undersampled. To address the sampling issue, future studies should
287 consider subsampling larger items with nonselective methodology such as suction.

288 However, it is also possible that there is a threshold debris size beyond which fish and
289 decapod predators suppress prey taxa diversity through direct predation and/or nonconsumptive
290 predator effects (Matassa and Trussell 2011). Some epipelagic fishes preferentially associate
291 with fouled rafting objects as opposed to unfouled rafting objects, suggesting that some of these
292 fishes may prey on rafting invertebrates (Nelson 2003, Thiel & Gutow 2005b), though other
293 studies have not found significant predation on the fouling community (Ibrahim et al. 1996;
294 Nelson 2003; Vassilopoulou et al. 2004). Most fishes observed in this study were associated with
295 the three net and rope masses, with the exception of one juvenile triggerfish (*Canthidermis*
296 *maculata*) on a bleach bottle and a school of sergeant majors (*Abudefduf* spp.) inside a plastic
297 crate. The net-associated fishes exhibited all three types of behavior identified by Hirotsuki
298 (1960) for macroalgae-associated fishes: staying almost exclusively within the net mass, such as

299 the sargassum frogfish (*Histrion histrio*); remaining underneath or around the mass in close
300 association, such as the sergeants; and swimming around the mass without close association,
301 such as the mahi mahi (*Coryphaena hippurus*). We also observed fish entangled in net masses
302 that were still alive, recently dead, and partially decomposed. The conspicuously low abundance
303 or absence of some species such as *Lepas* spp. and *Halobates* spp. eggs on net masses compared
304 to isolated fragments may be partially attributed to these net-mass associated fishes. For
305 example, the forward half of a small fishing boat floating upright in the western Pacific had more
306 than 50 associated individual fish, but very little attached biota (M.E. pers. obs.).

307 Plastic-associated rafting organisms may also be impacting the pelagic ecosystem by
308 reworking the organic particle size spectrum through ingestion and egestion (Mook 1981).
309 Suspension-feeding rafting organisms prey on a variety of particle sizes, from 3-5 μm for *Mytilus*
310 mussels (Lesser et al. 1992), 10-20 μm for bryozoans (Pratt 2008), 20-125 μm for caprellid
311 amphipods (Caine 1977), and 0.5 to more than 1 mm for lepadid barnacles and hydroids (Evans
312 1958; Boero et al. 2007; Goldstein and Goodwin 2013). This size range encompasses much of
313 the non-microbial organic particle size spectrum of the oligotrophic North Pacific (Sheldon et al.
314 1972). Since organic particle size determines whether energy flows into the microbial loop or
315 into the metazoan food web, large-scale alterations in particle size could substantially influence
316 the species composition of the North Pacific Subtropical Gyre (Karl et al. 2001). Future research
317 should also consider phytoplankton and microbial interactions with pelagic plastic macrodebris
318 (Maso et al. 2003; Zettler et al. 2013; Carson et al. 2013).

319 Though the majority of plastic debris items in the North Pacific are small fragments
320 (Goldstein et al. 2013), we found in this study that such particles carry few taxa, most of which
321 are known subtropical rafters such as *Jellyella* or *Membranipora* bryozoans. We found the

322 majority of displaced taxa on large items such as net balls, though the coral pathogen
323 *Halofolliculina* spp. was found on medium-sized plastic fragments (0.03-0.1 m²). Species
324 introductions from beached debris are most likely to occur on surfaces similar to the hard raft
325 substrate (i.e. bedrock shorelines) and during large debris deposition events (i.e. storms). While
326 debris removal operations are important to engaging the public on marine debris issues, they are
327 unlikely to significantly reduce the chances of non-native species introductions from plastic
328 debris. This is because coastal cleanups frequently occur on sandy beaches that are inherently
329 inhospitable to rafting organisms, and at pre-determined dates unlikely to coincide with major
330 debris deposition events. While some rapid-response operations to large debris beachings, such
331 as ships and docks originating from the 2011 Japanese tsunami event, may have been effective in
332 preventing species introductions in limited circumstances, large-scale debris cleanup on rocky,
333 remote shores is impracticable. Efforts to prevent debris input from both coastal sources (e.g.,
334 urban areas) and ocean sources (e.g., fishing debris) are likely the most efficient means of
335 controlling debris-mediated species introductions.

336 Durable plastic "islands" are hosts to a diversity of coastal organisms in the pelagic
337 environment, but the ecological role of plastic-associated rafting assemblages on the open ocean
338 remains unclear. Whether or not the plastic rafts introduce new species to distant coastal regions,
339 the consequences of these "misplaced" organisms to open-ocean ecosystems, especially in
340 debris-accumulation zones, merits further study. However, any potential impacts of the debris-
341 associated rafting community on coastal or pelagic ecosystems can be most effectively limited
342 by an overall reduction in the quantity of plastic pollution introduced into the marine
343 environment.

344

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362

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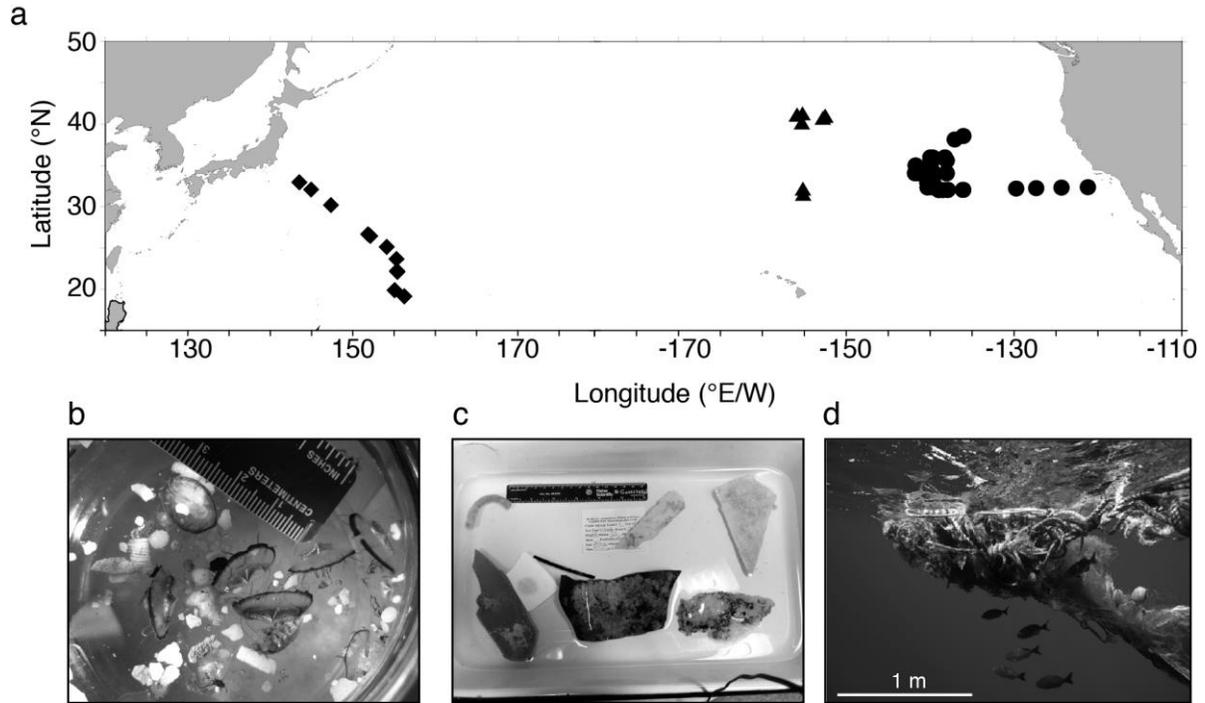


Figure 1. Map of sampling locations and photos of representative plastic debris

a) Locations of debris collection in 2009 (circles), 2011 (triangles), and 2012 (diamonds). b)

Small plastic fragments intermixed with the chondrophore *Verella verella*; collected 10 August

2009, 03:57 GMT, 32° 37.91' N, 140° 18.61' W. c) Medium plastic fragments with 15-cm ruler;

collected 11 August 2009, 07:30 GMT, 32° 54.99' N, 140° 19.81' W. d) A large tangle of

intermixed fishing-related nets, ropes and buoys along with other hard plastic debris (“rope

clump”); collected 12 May 2012, 03:00 GMT, 22° 13.35' N, 155° 21.17' E.

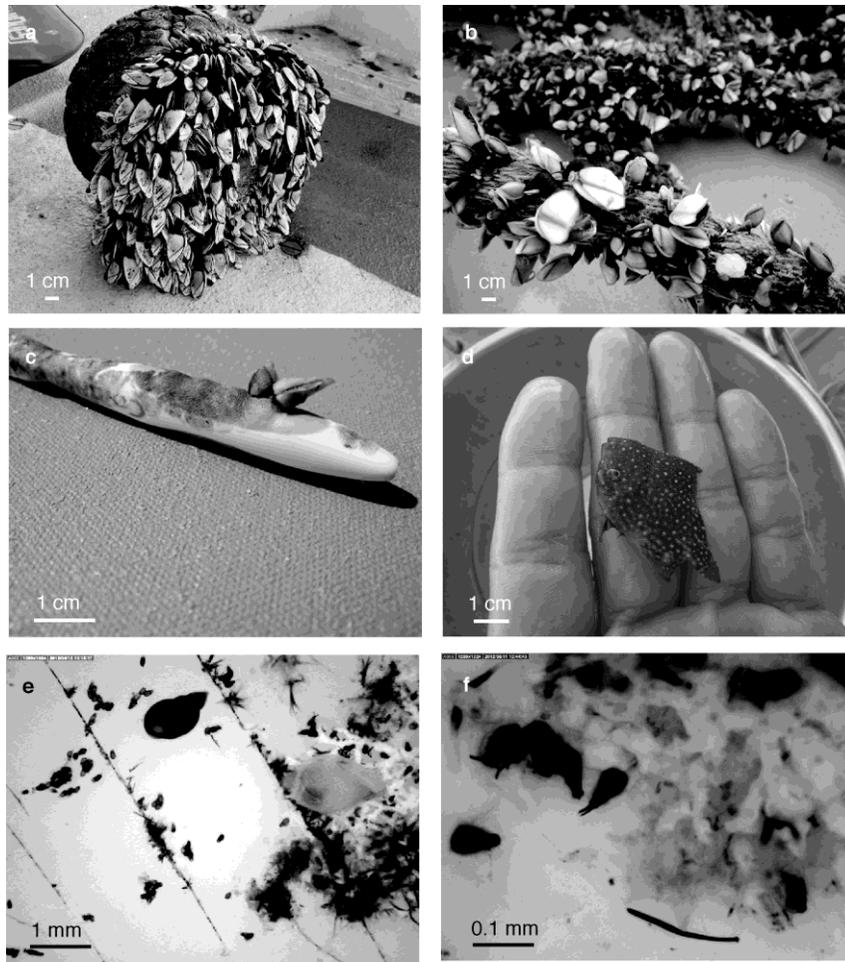


Figure 2. Photos of assorted debris

a) *Lepas* barnacles growing on buoy; collected 22 June, 2012, 02:00 GMT, 29° 11.9' N, 170°

35.2' E. b) *Lepas* barnacles growing on a rope; collected 14 May, 2012, 20:00 GMT, 26° 26.56'

N, 152° 07.44' E. c) Two *Lepas* barnacles and membraniporid bryozoans growing on a

toothbrush handle, collected 17 June, 2012, 02:00 GMT, 15° 26.3' N, 150° 30.0' E. d) A juvenile triggerfish *Canthidermis maculata* found associated with a bleach bottle, collected 12 May,

2012, 21:00 GMT at 22° 11.06' N, 155° 22.07' E. e) Close view of fragment showing

folliculinid ciliates and other organisms; collected 10 May, 2012, 22:15 GMT, 19° 53.05' N,

155° 04.22' E. f) Close view of folliculinid ciliates showing the two pericytostomial wings

extending from the lorica, collected 10 May, 2012, 22:15 GMT, 19° 53.05' N, 155° 04.22' E.

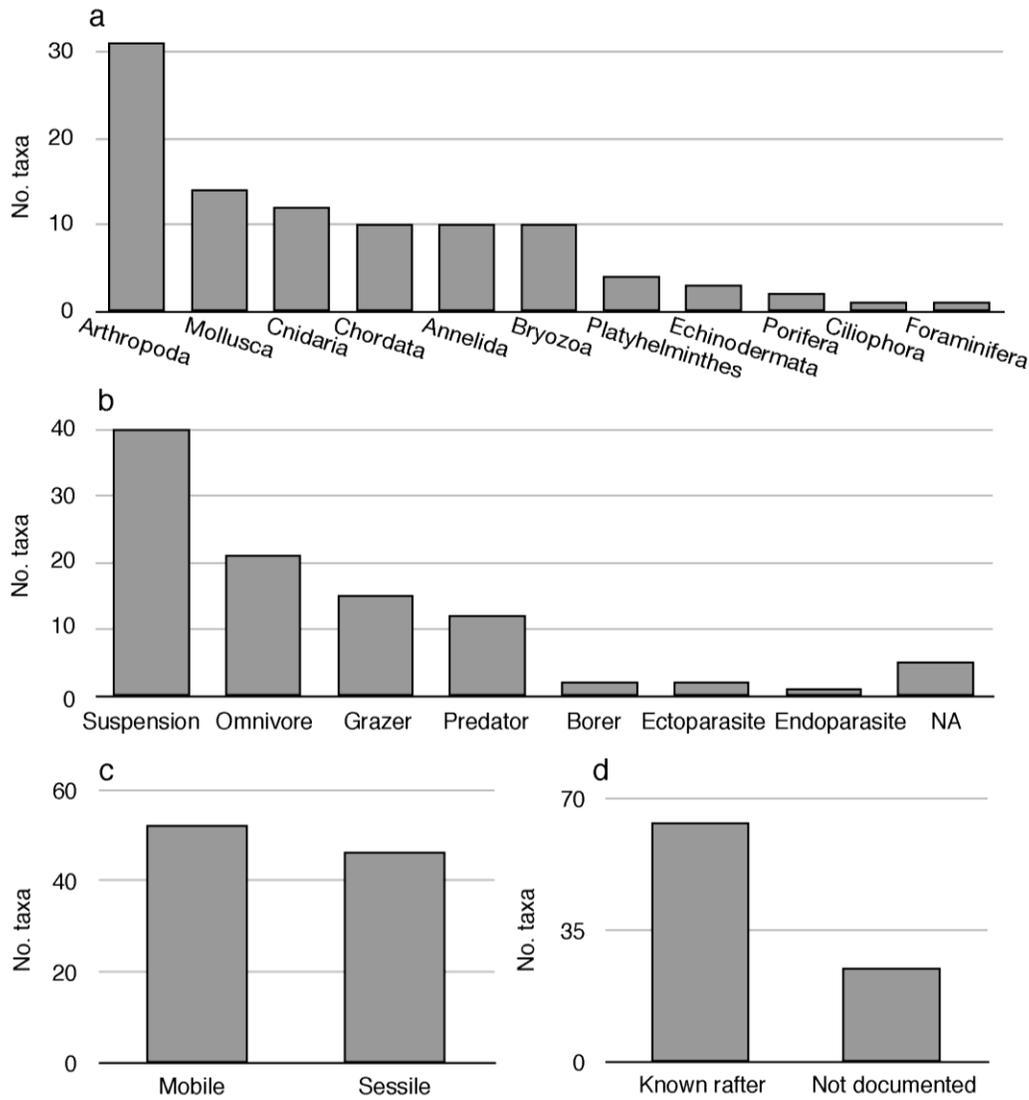


Figure 3. Characteristics of rafting taxa

a) Phyla found on or around floating plastic debris. b) Feeding types of rafting taxa. NA denotes eggs. c) Mobile taxa vs. sessile taxa. Fishes are excluded. d) Taxa that have previously been documented to occur in rafting communities vs. taxa that have not been documented. There was no statistical difference between cruise years/locations (Chi-square test, $P > 0.5$ for all tests) for these analyses, so data from all cruises were combined in this figure. N=95 taxa.

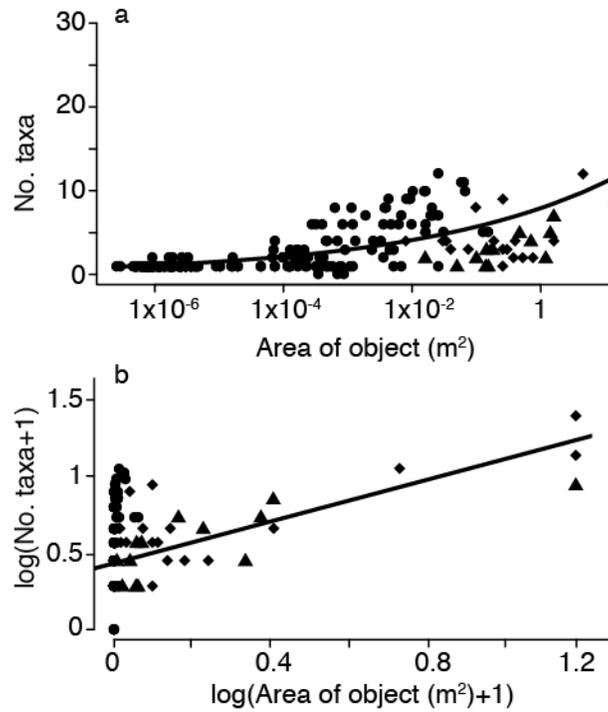


Figure 4. Number of taxa vs. surface area (m²) of debris object

a) Semilog plot. Solid line is an exponential non-linear least squares regression. Kendall's tau, $\tau=0.555$, $P<0.001$. b) Log-log plot. Solid line is a linear regression (Linear regression, $r^2=0.169$, $F_{1,66}=48.69$, $P<0.001$). Symbols in both plots correspond to year and location of collection: eastern Pacific 2009 is shown in circles, eastern Pacific 2011 in triangles, and western Pacific 2012 in diamonds. Note that many of the symbols denoting small plastic objects overlap, making the sample size hard to discern visually. $N=242$ debris objects.

Table 1. Rafting taxa

Years observed are a=Eastern Pacific 2009; b=Eastern Pacific 2011; c=Western Pacific 2012. Previously documented as rafting are N=Not listed as rafting in the scientific literature, 1=listed in Thiel & Gutow 2005b, 2=Lovely 2005, 3=Carter et al. 2010, 4=Matthews 1963, 5=Riemann-Zürneck 1998, 6=Emerson & Chaney 1995, 7=Bryan et al. 2012, N/A = fishes.

Phylum	Class	Order	Finest taxon Ided	Year observed	Previously documented as rafting
Annelida	Polychaeta	Aciculata	<i>Eunice</i> spp.	c	1
Annelida	Polychaeta	Amphinomida	<i>Amphinome rostrata</i>	c	1
Annelida	Polychaeta	Amphinomida	<i>Hipponoe gaudichaudi</i>	a,b	1
Annelida	Polychaeta	Phyllodocida	<i>Halosydna</i> spp.	b	N
Annelida	Polychaeta	Phyllodocida	Nereididae	c	1
Annelida	Polychaeta	Phyllodocida	<i>Nereis</i> spp.	c	1
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	c	1
Annelida	Polychaeta	Sabellida	<i>Salmacina</i> spp.	c	N
Annelida	Polychaeta	Sabellida	Subfamily Serpulinae	c	1
Annelida	Polychaeta	Sabellida	Subfamily Spirorbinae	a,c	1
Arthropoda	Malacostraca	Amphipoda	<i>Caprella</i> spp.	a,c	1
Arthropoda	Malacostraca	Amphipoda	<i>Elasmopus</i> spp.	a	1
Arthropoda	Malacostraca	Amphipoda	Hyalidae	a	1
Arthropoda	Malacostraca	Amphipoda	Isaeidae	b	N
Arthropoda	Malacostraca	Amphipoda	Pleustidae	c	N
Arthropoda	Malacostraca	Amphipoda	Stenothoidae	a	1
Arthropoda	Malacostraca	Amphipoda	Suborder Gammaridea	c	1
Arthropoda	Malacostraca	Decapoda	<i>Chorilia</i> spp.	c	N
Arthropoda	Malacostraca	Decapoda	Superfamily Majoidea	c	1
Arthropoda	Malacostraca	Decapoda	Megalopae	b	1
Arthropoda	Malacostraca	Decapoda	<i>Palaemon affinis</i>	c	1
Arthropoda	Malacostraca	Decapoda	<i>Pilumnus</i> spp.	c	N
Arthropoda	Malacostraca	Decapoda	<i>Plagusia</i> spp.	c	1
Arthropoda	Malacostraca	Decapoda	<i>Plagusia squamosa</i>	a	1
Arthropoda	Malacostraca	Decapoda	<i>Planes cyaneus</i>	a,c	1
Arthropoda	Malacostraca	Decapoda	<i>Planes minutus</i>	a	1
Arthropoda	Malacostraca	Decapoda	<i>Planes</i> spp.	b,c	1
Arthropoda	Malacostraca	Isopoda	Cirolanidae	a	1
Arthropoda	Malacostraca	Isopoda	<i>Idotea</i> spp.	a,b,c	1
Arthropoda	Malacostraca	Isopoda	Sphaeromatidae	a	1
Arthropoda	Maxillopoda	Harpacticoida	Harpacticoida	a	1
Arthropoda	Maxillopoda	Kentrogonida	<i>Heterosaccus</i> spp.	c	N
Arthropoda	Maxillopoda	Lepadiformes	Barnacle cyprids	a	1
Arthropoda	Maxillopoda	Lepadiformes	<i>Lepas anitifera</i>	a,c	1
Arthropoda	Maxillopoda	Lepadiformes	<i>Lepas pacifica</i>	a	1
Arthropoda	Maxillopoda	Lepadiformes	<i>Lepas</i> spp.	a,b,c	1
Arthropoda	Maxillopoda	Sessilia	(<i>Amphi</i>) <i>balanus amphitrite</i>	b	1
Arthropoda	Maxillopoda	Sessilia	<i>Chthamalus</i> spp.	c	N
Arthropoda	Maxillopoda	Sessilia	<i>Megabalanus rosa</i>	c	N

Table 1. Rafting taxa, continued.

Phylum	Class	Order	Finest taxon Ided	Year observed	Previously documented as rafting
Arthropoda	Pycnogonida	Pantopoda	<i>Phoxichilidium quadridentatum</i>	a	N, may encyst in hydroids ²
Arthropoda	Pycnogonida	Unknown	Unknown	c	1
Bryozoa	Gymnolaemata	Cheilostomatida	<i>Bugula</i> spp.	a,b,c	1
Bryozoa	Gymnolaemata	Cheilostomatida	<i>Jellyella eburnea</i>	a	1
Bryozoa	Gymnolaemata	Cheilostomatida	<i>Jellyella tuberculata</i>	a	1
Bryozoa	Gymnolaemata	Cheilostomatida	<i>Jellyella/Membranipora</i>	b,c	1
Bryozoa	Gymnolaemata	Cheilostomatida	<i>Membranipora tenella</i>	a	1
Bryozoa	Gymnolaemata	Ctenostomatida	<i>Bowerbankia</i> spp.	a	1
Bryozoa	Gymnolaemata	Ctenostomatida	<i>Victorella</i> spp.	a	N, may disperse through fragmentation of substrate ³
Bryozoa	Stenolaemata	Cyclostomatida	<i>Filicrisia</i> spp.	a	N
Bryozoa	Stenolaemata	Cyclostomatida	<i>Stomatopora</i> spp.	a	N
Bryozoa	Stenolaemata	Cyclostomatida	<i>Tubulipora</i> spp.	a	1
Chordata	Perciformes	Actinopterygii	<i>Abudefduf</i> spp.(<i>vaigiensis</i> ?)	b,c	N/A
Chordata	Perciformes	Actinopterygii	<i>Canthidermis maculata</i>	c	N/A
Chordata	Perciformes	Actinopterygii	<i>Chirolophis</i> spp.	c	N/A
Chordata	Perciformes	Actinopterygii	<i>Coryphaena hippurus</i>	b	N/A
Chordata	Perciformes	Actinopterygii	<i>Elagatis bipinnulata</i>	b	N/A
Chordata	Perciformes	Actinopterygii	<i>Histrio histrio</i>	c	N/A
Chordata	Perciformes	Actinopterygii	<i>Kyphosus</i> spp.(<i>vaigiensis</i> ?)	b,c	N/A
Chordata	Perciformes	Actinopterygii	<i>Meiacanthus</i> spp.	c	N/A
Chordata	Perciformes	Actinopterygii	<i>Seriola rivoliana</i>	c	N/A
Chordata	Unknown	Unknown	Beige fish eggs	c	1
Chordata	Unknown	Unknown	Blue fish eggs	c	1
Chordata	Unknown	Unknown	Fish eggs	a,b	1
Ciliophora	Heterotrichea	Heterotrichida	<i>Halofolliculina</i> spp.	c	N on plastic, documented on wood ⁴
Cnidaria	Anthozoa	Actinaria	Actiniidae	b	1
Cnidaria	Anthozoa	Actinaria	<i>Anthopleura</i> spp.	a,b	N, may disperse through detachment ⁵
Cnidaria	Anthozoa	Actinaria	<i>Calliactus</i> sp.	c	7
Cnidaria	Anthozoa	Actinaria	<i>Metridium</i> spp.	a	N, may disperse through detachment ⁵
Cnidaria	Anthozoa	Actinaria	Hormathiidae	c	1

Table 1. Rafting taxa, continued.

Phylum	Class	Order	Finest taxon Ided	Year observed	Previously documented as rafting
Cnidaria	Anthozoa	Scleractinia	stony coral	b	1
Cnidaria	Hydrozoa	Leptothecata	<i>Clytia gregaria</i>	a	N, though 9 other <i>Clytia</i> species documented as rafting ¹
Cnidaria	Hydrozoa	Leptothecata	<i>Obelia</i> spp.	a	1
Cnidaria	Hydrozoa	Leptothecata	<i>Plumularia setacea</i>	a	1
Cnidaria	Hydrozoa	Unknown	Hydroid	b,c	1
Echinodermata	Ophiuroidea		<i>Ophiuroidea</i> spp. 1	c	
Echinodermata	Ophiuroidea		<i>Ophiuroidea</i> spp. 2	c	
Echinodermata	Ophiuroidea		<i>Ophiuroidea</i> spp. 3	c	
Foraminifera	Polythalamia	Rotallida	<i>Planulina ornata</i>	a	N
Mollusca	Bivalvia	Arcoida	Arcidae	c	N
Mollusca	Bivalvia	Myoida	<i>Teredo</i> spp.	c	1
Mollusca	Bivalvia	Myoida	<i>Zirfaea</i> spp. (<i>pilsbryi</i> ?)	b	N
Mollusca	Bivalvia	Mytiloida	<i>Mytilus galloprovincialis</i>	a,c	1
Mollusca	Bivalvia	Ostreoida	<i>Crassostrea gigas</i>	b,c	1
Mollusca	Bivalvia	Pectinoida	<i>Chlamys</i> spp.	c	1
Mollusca	Bivalvia	Pteroida	<i>Pinctada</i> spp.	c	1
Mollusca	Bivalvia	Unknown	Lower valve of oyster	c	1
Mollusca	Gastropoda	Caenogastropoda	<i>Litiopa melanostoma</i>	c	1
Mollusca	Gastropoda	Littorinimorpha	<i>Erronea</i> spp.	c	N, may have widespread larval transport ⁶
Mollusca	Gastropoda	Nudibranchia	<i>Fiona pinnata</i>	a,b,c	1
Mollusca	Gastropoda	Nudibranchia	<i>Fiona pinnata</i> eggs	a	1
Mollusca	Gastropoda	Pleurobranchomorpha	<i>Berthella</i> spp.	c	N
Mollusca	Gastropoda	Superfamily Pyramidelloidea	<i>Odostomia (Evalea) tenuisculpta</i>	a	N
Platyhelminthes	Rhabditophora	Polycladida	Rhabditophora	c	1
Platyhelminthes	Rhabditophora	Rhabdocoela	Rhabdocoela	c	1
Platyhelminthes	Turbellaria	Unknown	Flatworm	a,b	1
Platyhelminthes	Turbellaria	Unknown	Flatworm	b	1
Porifera	Calcarea	Leucosolenida	<i>Sycon</i> spp.	b,c	N
Porifera	Demospongiae	Halichondrida	<i>Halichondria panacea</i>	a	N

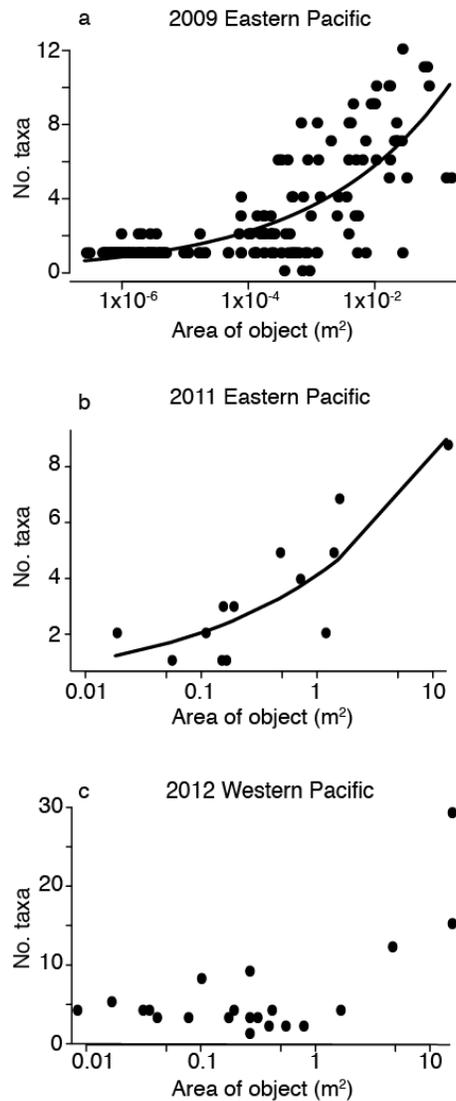


Figure S1. Semilog plots of taxa vs. surface area (m²) of debris object, by cruise

Solid line is an exponential non-linear least squares regression. a) 2009 Eastern Pacific

(Kendall's tau, $\tau=0.561$, $N=208$, $P<0.001$); b) 2011 Eastern Pacific (Kendall's tau, $\tau=0.650$,

$N=13$, $P=0.003$); c) 2012 Western Pacific (Kendall's tau, $\tau=0.062$, $N=21$, $P=0.710$). No fit line is

included in (c) due to the lack of a significant correlation, which was caused by limited sample

size of large objects. Differences in x-axis scale between 2009 and 2011/2012 are due to

different sampling methodologies.

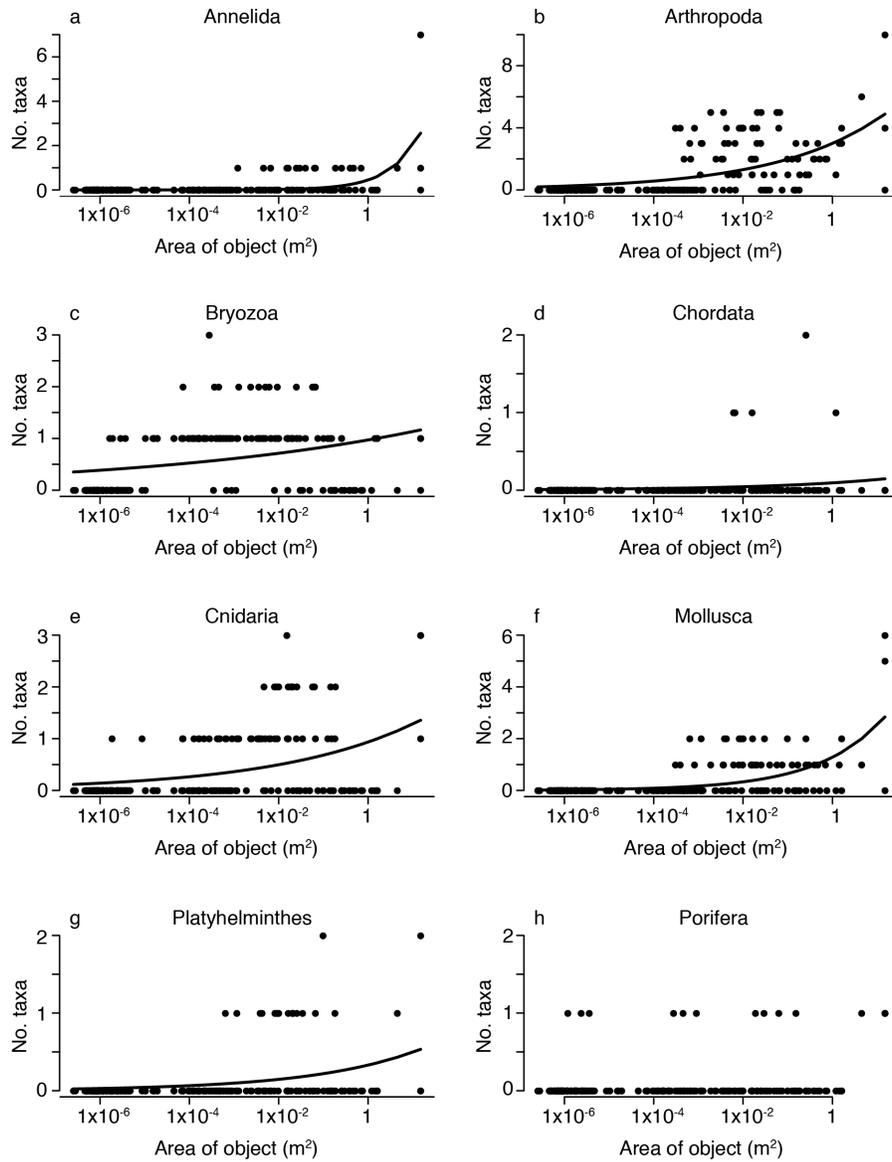


Figure S2. Semilog plots of taxa vs. surface area (m²) of debris object, by phylum

Solid line is an exponential non-linear least squares regression. All following statistics are for Kendall's tau, with sample size $N=242$. a) Annelida, $\tau=0.304$, $P<0.001$; b) Arthropoda, $\tau=0.526$, $P<0.001$; c) Bryozoa, $\tau=0.447$, $P<0.001$; d) Chordata, $\tau=0.142$, $P=0.007$; e) Cnidaria, $\tau=0.394$; $P<0.001$; f) Mollusca, $\tau=0.417$, $P<0.001$; g) Platyhelminthes, $\tau=0.267$, $P<0.001$; h) Porifera, $\tau=0.163$, $P=0.002$. If the 4 largest objects are excluded, all relationships remain significant with the exception of Porifera ($\tau=0.082$, $P=0.121$).