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Boring crustaceans damage polystyrene floats under docks polluting marine waters with microplastic

Timothy M. Davidson *

Aquatic Bioinvasion Research and Policy Institute, Environmental Science and Management, Portland State University (ESM), P.O. Box 751, Portland, OR 97207, USA

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A B S T R A C T

Boring isopods damage expanded polystyrene floats under docks and, in the process, expel copious numbers of microplastic particles. This paper describes the impacts of boring isopods in aquaculture facilities and docks, quantifies and discusses the implications of these microplastics, and tests if an alternate foam type prevents boring. Floats from aquaculture facilities and docks were heavily damaged by thousands of isopods and their burrows. Multiple sites in Asia, Australia, Panama, and the USA exhibited evidence of isopod damage. One isopod creates thousands of microplastic particles when excavating a burrow; colonies can expel millions of particles. Microplastics similar in size to these particles may facilitate the spread of non-native species or be ingested by organisms causing physical or toxicological harm. Extruded polystyrene inhibited boring, suggesting this foam may prevent damage in the field. These results reveal boring isopods cause widespread damage to docks and are a novel source of microplastic pollution.

1. Introduction

Marine borers can cause substantial damage to marine structures. The most extensive and costly damage occurs in wooden structures by teredinid bivalves (shipworms) and isopod crustaceans (Cragg et al., 1999; Neily, 1927). For example, the non-native shipworm *Teredo navalis* destroyed the timber pilings and supports of docks in San Francisco Bay causing nearly 50 structures to collapse and causing $615 million in damages (Cohen and Carlton, 1995; Miller, 1926; Neily, 1927). Crustacean borers are also very destructive (Cookson et al., 1986; Cragg et al., 1999; Kofoid and Miller, 1927), especially in Australia where timber replacement costs from marine borers are around $20 million per year (in 1986 AUD dollars; Cookson et al., 1986). Moreover, borers can attack non-wooden structures as well, such as rock sea walls (Chilton, 1919), concrete structures (Kofoid and Miller, 1927), and even steel support beams (Irwin, 1953).

Burrowing sphaeromatid isopods bore into numerous substrata used in marine structures and facilities in brackish temperate and tropical regions (Carlton, 1979; Chilton, 1919; Cragg et al., 1999; Kofoid and Miller, 1927). Boring isopods are native to the Indo and West Pacific but are non-native in North America and perhaps in the Caribbean (Carlton and Iverson, 1981; Carlton and Ruckelshaus, 1997; Harrison and Holdich, 1984). These estuarine isopods tolerate a wide range of salinities (0–43 PSU, Estevez, 1994; Riegel, 1959) and temperatures (5–42 °C; Jansen, 1971). However, they suffer mortality after several days at the lowest salinity (0 PSU) or temperature (5 °C; Jansen, 1971; Riegel, 1959). In the field, the boring isopods *Sphaeroma quoianum*, *Sphaeroma terebrans*, and *Sphaeroma peruvianum* are most often found between 5 and 31 PSU salinity (Davidson, 2008; Davidson et al., 2008, unpublished data). The burrowing isopods *S. quoianum* and *S. terebrans* live for 12–18 months and 10 months, respectively, and can produce up to two cohorts before dying (Schneider 1976, Thiel, 1999).

These borers are especially destructive to expanded polystyrene floats (commonly known as Styrofoam) used in many docks. Densely clustered colonies of these direct-developing isopods perforate the submerged surface of the float and appear to reduce its functionality. While burrows are initially shallow (less than 30 mm deep, and rarely exceeding 60 mm; Davidson and de Rivera, 2012; Perry and Brusca, 1989; Talley et al., 2001), subsequent generations and colonizers extend and build from old burrows, creating an interconnected burrow network (as described by Talley et al., 2001; Thiel, 1999). This extensive network substantially reduces the density of the outer 60 mm of the float, making the foam noticeably weaker and more susceptible to breakage. As the outer surface is removed, additional area of the float becomes vulnerable to attack. Boring sphaeromatid isopods are filter feeders that excavate burrows for habitat (Rotramel, 1975; Si et al., 2002); therefore, any consumption of excavated material is likely

* Present address: Smithsonian Tropical Research Institute, Apartado Postal 0843-03092, Balboa, Ancon, República de Panamá. Tel.: +507 212 8830; fax: +507 212 8790.

E-mail address: DavidsonT@si.edu

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incidental (Messana et al., 1994; Rotramel, 1975; Si et al., 2002). While some floats are encapsulated with hard plastic shells or sheets, many docks or facilities either do not use these materials, or the encapsulation materials are damaged and vulnerable to isopod burrowing (per. obs.).

Minute plastic particles are created through the boring process of polystyrene floats by *S. quoianum* (Carlton, Chang, and Wells, unpublished, as cited in Carlton and Ruiz, 2005), *S. terebrans*, and *S. peruvianum* (per. obs.). Like other microplastics (defined as <5 mm in diameter, Arthur and Bamford, 2009) in the marine environment, these particles may have detrimental effects to marine organisms (Carpenter et al., 1972; Cole et al., 2011; Gregory, 1996; Thompson et al., 2004). Plastics persist for hundreds to thousands of years in normal oceanic conditions (Barnes et al., 2009). Also, polystyrene fragments and other minute plastics in the marine environment are readily colonized by biofilm and other organisms causing them to sink (Barnes, 2002; Gregory, 2009; Ye and Andrady, 1991). Thus, these particles may interact with benthic (Graham and Thompson, 2009; Thompson et al., 2004) and pelagic organisms (Boerger et al., 2010; Carpenter et al., 1972; Davison and Asch, 2011). Ingested microplastics may cause both toxicological effects by transmitting bioaccumulating toxins (Mato et al., 2001; Teuten et al., 2009) and possibly physical effects by occluding feeding structures or inducing a false indication of satiation.

The damage caused by boring isopods to polystyrene floats under floating docks can result in economic costs and contribute to microplastic pollution. This paper reports observations of the destructive effects of boring isopods on foam floats, quantifies the density of burrows and individuals in floats, quantifies the abundance of plastic particles created from the boring process, and discusses the morphology and ecological implications of the plastic particles created through the boring process. Furthermore, results of an experiment examining how different polystyrene float types may prevent damage by borers are presented. Together these observations, surveys, and experimental results reveal (a) the damaging effects of non-native and native borers on the floatation in docks, (b) how a non-native species contributes to microplastic pollution, and (c) approaches to reduce these effects in the many bays that harbor populations of boring isopods.

2. Methods

2.1. Observations of isopods attacking floats

Shoreline surveys were conducted in Yaquina Bay, Oregon, USA, and in Budai Township and Tainan, Taiwan. Both the high tide lines and docks and marinas in intertidal and shallow subtidal areas were examined for damaged polystyrene flotsam or floats; populations of *Sphaeroma* sp. occurring in adjacent substrata were also noted. Search effort was focused on areas between 5 and 31 PSU, where boring isopod populations are most often found (Davidson, 2008; Davidson et al., 2008). Polystyrene floats and flotsam were considered burrowed by sphaeromatids if they harbored living or dead individuals in their burrows or if vacant burrows were consistent with the morphology of burrows created by sphaeromatid isopods: (i) vermiform burrows with smooth walls, (ii) circular diameters between 2 and 10 mm, and (iii) up to 77 mm deep, and (iv) mostly straight without abrupt changes in direction (Barrows, 1919; Davidson and de Rivera, 2012; Talley et al., 2001). To my knowledge, no other boring organism creates burrows consistent with this morphology and the burrows of other organisms (e.g. small grapsid crabs) are rare (per. obs.). Furthermore, these surveys are supplemented with additional reports of isopod burrowing from both published sources and unpublished observations.

2.2. Mean density of individuals and burrows of S. quoianum in expanded polystyrene flotsam

Between February 2005 and May 2006, samples of burrowed expanded polystyrene floating dock flotsam encountered during surveys of Coos Bay ($n = 18$ pieces) were collected. Each piece was photographed with a haphazardly placed 10×10 cm quadrat in the burrowed area of the float. The number of quadrats photographed varied concomitantly with the size of the expanded polystyrene flotsam found. One quadrat was used to estimate the burrow density of small pieces (30–60 cm long) and between 6 and 50 quadrats for larger pieces (entire floats >60–100 cm long). Digital analysis software, ImageJ 3.0 version 1.49u, was then used to count the total numbers of burrows per quadrat.

Burrowed expanded polystyrene float mimics were deployed in Coos Bay, Oregon for 1 year (2005–2006) to provide an estimate for how many isopods inhabit expanded polystyrene floats. The float mimics were constructed of a burrowed expanded polystyrene float found in the field (devoid of isopods). Blocks were cut to $10 \times 10 \times 8$ cm (length, width, depth). Each block was surrounded in polyethylene tape exposing only the burrowed 100 cm^2 face. Burrow densities in these mimics were 64.2 ± 2.3 burrows per 100 cm^2 (mean ± 95% CI). The blocks were affixed facing downwards to weighted PVC tubing and placed around a length of rebar planted into the ground. The weighted PVC tube kept the orientation of the blocks pointing downward while allowing the floats to move up and down with the tide along the rebar pole. These expanded polystyrene dock mimics were deployed in six different locations with salinity between 10 and 31 PSU in Coos Bay, Oregon.

2.3. Quantity and morphology of the plastic particles created during boring by S. quoianum

A lab experiment was conducted to quantify the numbers of particles created by *S. quoianum* during the boring process (methodology described in detail in Davidson et al., in preparation). Small colonies of 20 adult isopods (7–12 mm in length) from Coos Bay, Oregon were placed inside cages with an expanded polystyrene foam block (800 cm^3) with one exposed surface (100 cm^2). Fifteen small holes (4 mm deep) were created in each block to prompt isopods to begin burrowing; these values were not included in the measurements of burrow length. Each cage was then submerged in a closed aerated aquarium at one of 13 water temperatures (7.5–25.2 °C) to vary burrowing intensity (Davidson et al., in preparation). Isopods were allowed to burrow for 2 months. At the end of the experiment, the number of burrows created and mean lengths were measured in each foam block and the plastic particles were collected by discharging the aquarium water through a 63 μm sieve. The particles were placed on a gridded paper filter (1 cm^2 grid) and agitated to help homogenize the distribution of particles on the grid. The total number of grid squares occupied by plastic particles was counted and then five subsamples (1 cm^2 squares) were randomly selected to be photographed using a digital microscope camera. The numbers of particles in each square subsample were counted using digital analysis software. The total number of particles created during the boring process in the different blocks was calculated by multiplying the mean number of particles per subsample (1 cm^2) by the total number of squares occupied by plastic particles. The relationship between the number of particles created per burrow and mean burrow length (total burrow length in a block/number of burrows created) was examined using ordinary least squares regression. The data were square-root transformed to meet assumptions of linearity, homogenous variance, normality, and reduce the influence of outliers. The lowest value appeared to be influential (Cook's Distance = 0.81), however, its removal did not substantially change the shape of the relationship (but reduced the R^2 to 0.67). This potentially influential value was retained since there was not a non-statistical reason to merit its removal.

To examine the morphology of the particles, particles from aquaria where adult individuals of *S. quoianum* (7–12 mm long) had burrowed into a block of expanded polystyrene were collected. The plastic particles and surrounding water were haphazardly collected from aquarium water and placed on a microscope slide. The particles were photographed using a digital camera attached to a light microscope (with a calibrated scale bar). Image analysis and preprocessing were completed using ImageJ. Images were preprocessed using the *Sharpen* and *Find Edges* functions to make the main body of the particle more conspicuous. The area (as measured by ImageJ), perimeter, longest axis (length), and the widest axis (orthogonal to the longest axis, width) of each of 200 particles was measured and the equivalent circular diameter calculated ($\mathrm{ECD} = \sqrt{\frac{4}{\pi} \cdot Area}$; Russ, 2007; Sprules et al., 1998). The ECD standardizes irregular objects to a standard circle to allow comparisons of objects of variable shape and orientation (Russ, 2007). All measurements were recorded from the areas of the particles that were solid and opaque; the many light, short, diaphanous plastic threads exuding from most sides were not included in measurements.

2.4. The effects of polystyrene float type on colonization by a non-native boring isopod

The effects of three different types of polystyrene floats on burrowing by *S. quoianum* were tested using a lab experiment in a Latin square design. One block of polystyrene ($5 \times 6 \times 12$ cm) was affixed vertically per cylindrical microcosm (946 ml). The treatments were: (a) expanded polystyrene (EPS; $n = 23$), (b) extruded polystyrene (XPS; $n = 22$), or (c) expanded polystyrene encapsulated with a damaged polyethylene cover (encapsulated EPS; 4 cm single tear at the bottom, mimicking wear and tear of encapsulation material exposed to boats and floating debris, $n = 23$). Thin polyethylene encapsulation sheeting was often used to encapsulate floats in floating docks in Coos Bay and other Pacific coast estuaries (per. obs.). While the use of encapsulation material over foam is mandatory in Oregon (G. Dolphin, per. comm.; Oregon Administrative Rule 250-014-0030), many docks do not use it or the material is degraded and torn (per. obs.). Each microcosm was filled with saltwater (25 PSU) and phytoplankton, their primary food source in nature, was periodically added for sustenance (Rotramel, 1975). Since *S. quoianum* is thigmotactic, a small divot was created in the bottom of each block to prompt isopods to start burrowing. One adult isopod between 7 and 12 mm in length was then added to each microcosm and allowed to burrow for 24 days. The status of the isopods (burrowing, not burrowing, moribund, or dead) was recorded each day for 15 days. The status of the isopods on days 19 and 24 (the last day of the experiment) were also noted.

A chi-square test (with 10,000 randomizations) was used to test if the total number of isopods that burrowed in a block differed among treatments. The differences in total burrow length and burrow use (the percent of the time isopods were present in burrows they created) between EPS and encapsulated EPS treatments were analyzed using Mann–Whitney tests since transformations failed to normalize the data. Statistical analysis of the XPS treatment data was unnecessary as burrowing was not observed.

3. Results

3.1. Damage to the dock floats of aquaculture facilities and marinas by sphaeromatid isopods

Damage from dense colonies of boring isopods was observed in aquaculture facilities in Yaquina Bay, Oregon, USA and Tainan, Taiwan. In Yaquina Bay, Oregon, colonies of the non-native isopod *S. quoianum* damaged the expanded polystyrene floats used by an aquaculture facility to raise oysters. Repair of the docks required removing around 60 heavily-riddled floats (each ~1 m long; Fig. 1A–C). Some floats still harbored dead isopods. The outer surface of many of the floats had become eroded, vacuous, and easily ablated by touching the surface. The attack was so concentrated in some floats that it reduced the normally rectangular shaped float to a t-shaped cross-section (Fig. 1B).

Similar patterns were observed in Tainan, Taiwan; fifteen floats removed from an adjacent aquaculture facility were found onshore and heavily riddled with isopod burrows (Fig. 1D–F). In Taiwan, the native isopod *S. terebrans* was likely responsible for the damage since this species was abundant in the mangroves lining the pond.

In addition to the above observations of isopods impacting these aquaculture facilities, field surveys revealed the presence of burrowed foam flotsam or floats in Yaquina Bay, several sites in Taiwan, and one site in Caribbean Panama. Five out of six sites in Yaquina Bay with foam flotsam or exposed floats accessible for examination were damaged by isopods. Burrowed floats were also observed in Taiwanese sites including flotsam in Kinmen Island (presumably washed ashore from neighboring Xiamen, mainland China), and two burrowed floats each in Budai Township and Tainan. Two small lightly burrowed floats were also observed at Galeta Point near Colon in Caribbean Panama. These floats were likely burrowed by *S. terebrans* since these isopods were abundant in the adjacent red mangroves.

Burrows and isopods were also found in high densities in expanded polystyrene foam flotsam and in float mimics. The foam collected from Coos Bay harbored thousands of burrows of *S. quoianum* per square meter (Table 1). Similarly, isopods were found in high densities in the experimental float mimics.

3.2. Quantity and morphology of the microplastic created by S. quoianum

The numbers of particles created per burrow were strongly related to the length of the burrow ($R^2 = 0.89$, $F = 85.8$, $P < 0.001$; Fig. 2). A minimum of 89 particles were created from a burrow 1.6 mm long and a maximum of 4630 particles were created from a burrow 17.4 mm long. The plastic particles created by *S. quoianum* were variable and irregular in shape (Fig. 3). Most of the plastic particles were roughly globular or rectangular in shape and lined with fine strands; others were highly irregular. The mean (±95% CI) maximum length of the particles was 462.6 ± 29.2 μm and mean maximum width (orthogonal to the maximum length) was 283.0 ± 19.0 μm (Fig. 4). The mean ECD was 255.1 ± 12.4 μm. The mean perimeter-area ratio was 0.033 ± 0.002, which was ~200% higher than a similar-sized circle (diameter = 255 μm, perimeter-area ratio = 0.016). While the histograms of the morphological characteristics were centered around the means described above, they were skewed to the right due to a few high values (Fig. 4).

3.3. The effects of polystyrene float type on colonization by a non-native boring isopod

The type of polystyrene float affected the frequency of burrowing, burrow length, and burrow use by *S. quoianum*. Isopods burrowed more often in expanded polystyrene (10 of 23 floats were burrowed, 43.5%) than damaged encapsulated expanded polystyrene (7/23, 30.4%) and extruded polystyrene (0/22, 0%; $\chi^2 = 10.3$, df = 2, $P = 0.006$). There was no difference in the frequency of burrowing between EPS and damaged encapsulated EPS ($\chi^2 = 0.89$, df = 1, $P = 0.35$). Isopods did not burrow into (hence did not use burrows) in the extruded foam treatment. While the

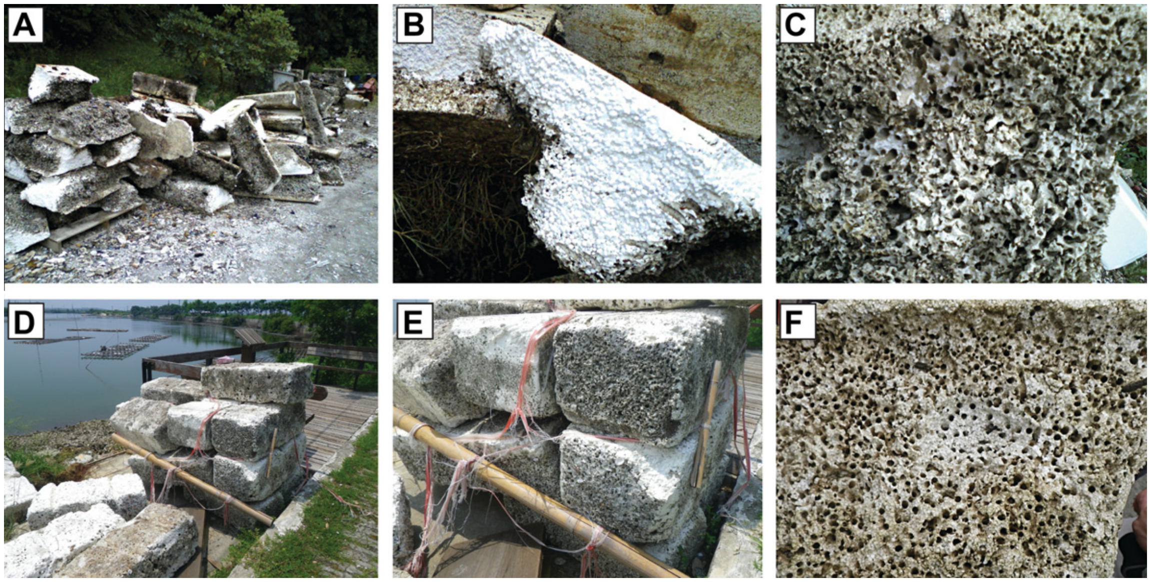

Fig. 1. Extensive burrowing by populations of boring isopods damaged the polystyrene floats in the docks used by aquaculture facilities in (A–C) Yaquina Bay, Oregon, USA (*Sphaeroma quoianum*; 7/15/2007) and (D–F) Tainan, Taiwan (presumably *Sphaeroma terebrans*; 8/5/2010). The floats in A and D were approximately 1 m and 2 m in length, respectively. Images in C and F are at differing scales, but the burrows pictured in these images are similar in size (8–10 mm).

Table 1
Mean, maximum, and minimum of densities of burrows and isopods (*Sphaeroma quoianum*) collected from expanded polystyrene floats ($n = 18$; burrow densities) and float mimics ($n = 6$; isopod densities) in Coos Bay, Oregon.

Density	Mean (±95% CI)	Max.	Min.
Burrows per m^2	7875 (±1687)	25,000	2400
Burrows per float[a]	23,413 (±5016)	74,322	7134
Isopods[b] per m^2	14,900 (±7576)	32,000	2400
Isopods per float	44,296 (±22,523)	95,133	7135

[a] Calculations were based on a float with the following dimensions: 244 × 122 × 46 cm; surface area ~3 m^2 assuming the outer 6 cm was vulnerable to burrowing damage.
[b] Isopod densities are based on the colonization of the outer 6 cm of expanded polystyrene float mimics ($n = 6$) deployed for 1 year.

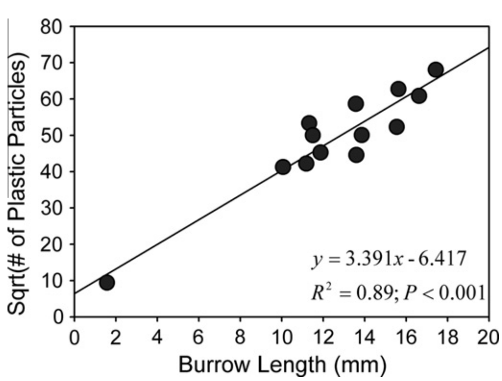

Fig. 2. The relationship between the numbers of plastic particles created (square-root transformed) per burrow and the mean length of burrows created by *Sphaeroma quoianum*.

expanded polystyrene had greater values in all measures than the encapsulated treatment, mean burrow length (±95% CI) was not significantly greater in the EPS (3.23 ± 1.49) than in the damaged encapsulated EPS (2.21 ± 1.49; $U = 311$, $P = 0.26$). Likewise, isopods did not use burrows significantly more in the EPS (13.52 ± 8.09) than the encapsulated EPS (9.14 ± 7.00; $U = 318$, $P = 0.19$).

4. Discussion

4.1. Damage to foam floats in aquaculture facilities and marinas by non-native and native boring isopods

The floats of docks and facilities in Asia, Australia, Central America, and North America suffered damage from burrowing sphaeromatids (Fig. 5, Table 2). These damaging effects are exemplified in the two aquaculture facilities examined. Dense colonies of boring isopods attacked the floats used in aquaculture facilities in Yaquina Bay, Oregon, USA and Tainan, Taiwan, forcing the replacement of floats and incurring economic costs. The burrow densities in these floats, foam flotsam, and float mimics exceeded many thousands per exposed square meter of foam. Floats inhabited by high densities of isopods were noticeably weaker and vacuous; the outermost surface was easily removed by hand. Given such a weakened surface, additional damage occurs to heavily burrowed floats when they are scoured by water movement or abraded by debris (per. obs.). Docks damaged by isopods have also been reported from Coos Bay and San Francisco, California (Carlton, per comm.; Cohen and Carlton, 1995; Davidson, 2008) with non-native populations of *S. quoianum*. Previous surveys of Coos Bay revealed a ten-meter section of a derelict dock riddled with burrows (Davidson, 2008) and another dock in a state of disrepair with the exposed floats burrowed by isopods (per. obs.). Likewise, a tugboat terminal in Coos Bay was abandoned when severe burrowing by isopods rendered it virtually inoperable (Carlton, per comm). While a previous study reported polystyrene foam (Styrofoam) was rarely inhabited compared to other substrata (Davidson, 2008), few docks accessible to surveying were available and thus may reflect low sampling effort. Four out of five surveyed docks with exposed floats exhibited burrowing damage consistent with *S. quoianum* (unpublished data from Davidson, 2008). Furthermore, Cohen and Carlton (1995) report the dock floats in marinas of San Francisco Bay were frequently riddled by *S. quoianum*. This report is consistent with accounts by Rotramel (1971), per comm who first observed extensive damage by *S. quoianum* in floating docks at Berkeley Marina (San Francisco, CA) in 1966. Damage to floats under docks was also noted in Moss Landing Harbor in 1998 (Elkhorn Slough, CA; Wasson, per comm).

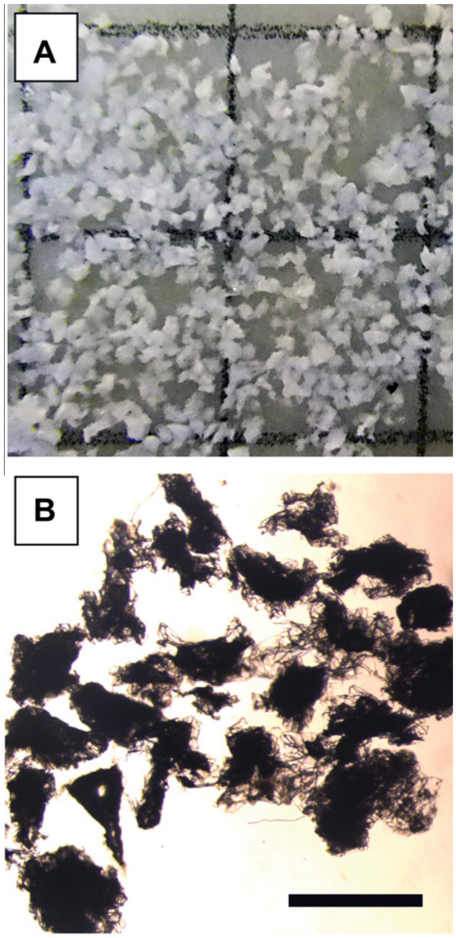

Fig. 3. Microscope images of the plastic particles created by *Sphaeroma quoianum* during the burrowing process into expanded polystyrene floats. The images are shown at two magnifications: (A) Each square in the image is 0.25 cm^2. (B) The scale bar in this image is 500 μm.

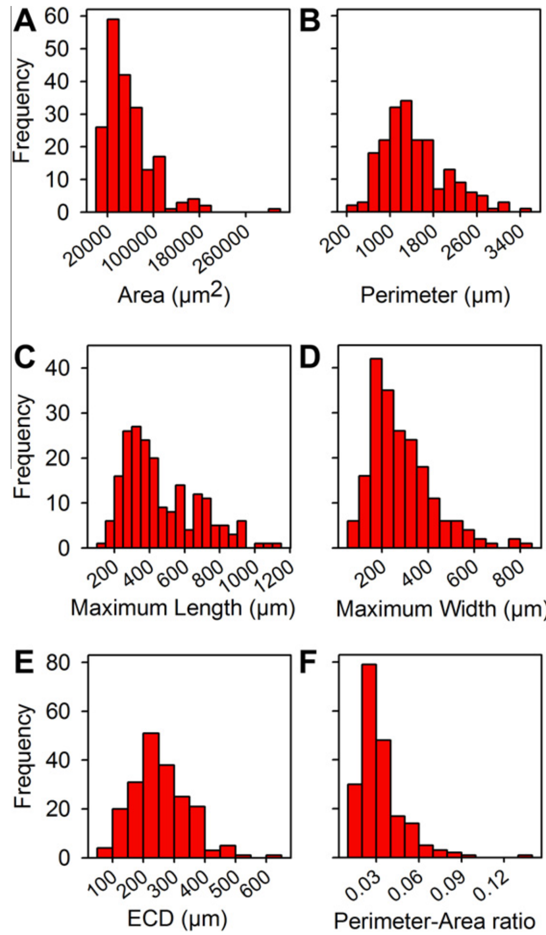

Fig. 4. Frequency histograms of the (A) area, (B) perimeter, (C) maximum length, (D) maximum width (orthogonal to the length measurement), (E) equivalent circular diameter (ECD) and (F) perimeter-area ratio of the microplastic particles created during burrowing by *Sphaeroma quoianum* in expanded polystyrene floats ($n = 200$).

Furthermore, the presence of large pieces of foam floats found throughout Coos Bay suggests rafting may be an important dispersal mechanism for the non-native *S. quoianum* and likely other sphaeromatids. Since isopod boring may facilitate the breakage of floats, large floating colonies may potentially be dispersed to new areas within a bay or possibly between bays. The movement of large colonies of hundreds or thousands of direct developing isopods may enhance invasion success in new locations (Johannesson, 1988; Thiel and Gutow, 2005).

The spread of *S. quoianum* to new estuaries may result in damage to floats under docks and facilities but may also have destructive effects to other estuarine habitats and substrata. By perforating saltmarsh banks with burrows, populations of *S. quoianum* appear to exacerbate erosion rates of saltmarshes (Carlton, 1979; Davidson and de Rivera, 2010; Talley et al., 2001); areas in saltmarsh banks inhabited by *S. quoianum* experience erosion rates 300% higher than adjacent unburrowed areas (Davidson and de Rivera, 2010). Burrowing by isopods also alters and damages other estuarine substrata (e.g. friable rocks, wood), and provides a novel habitat for other organisms including disproportionately large numbers of non-native species compared to other habitats (Davidson et al., 2010).

4.2. Microplastic pollution created by a non-native boring isopod

Boring by colonies of sphaeromatid isopods in expanded polystyrene floats can create millions of microplastic particles and may have negative effects to marine organisms. An individual of *S. quoianum* can create up to 4630 plastic particles when excavating a burrow 17.4 mm long. Extrapolating that estimate to a population of 100,000 (a density observed in a cubic meter of substrata, Davidson et al., 2010; or two floats, Table 1), the total number of particles created by 100,000 isopods each creating a burrow is 416.7 million. However, the mean burrow length (±95% CI) created by *S. quoianum* in the lab (22.6 ± 2.2 mm in the lab at 14 °C) and from field measurements (25.3 ± 17.5 mm; Davidson and de Rivera, 2012) are longer than the burrow lengths observed in this experiment. When estimating the number of plastic particles created using these mean values and the equation presented in Fig. 2 (and back transforming), one adult of *S. quoianum* would create between 4900 (±1.1) and 6300 (±2801) particles during the boring process (490–630 million per 100,000 isopods). While there is variation in the specific number of particles created in the boring process, these estimates reveal the extremely high magnitude of microplastic that is created through the boring process by this non-native isopod and likely other boring isopods.

4.3. Potential implications of microplastic pollution

Microplastics, similar in size to those created by this bioeroder, persist in the marine environment (Barnes et al., 2009) and may be consumed or colonized by numerous species (Gregory, 2009; Cole

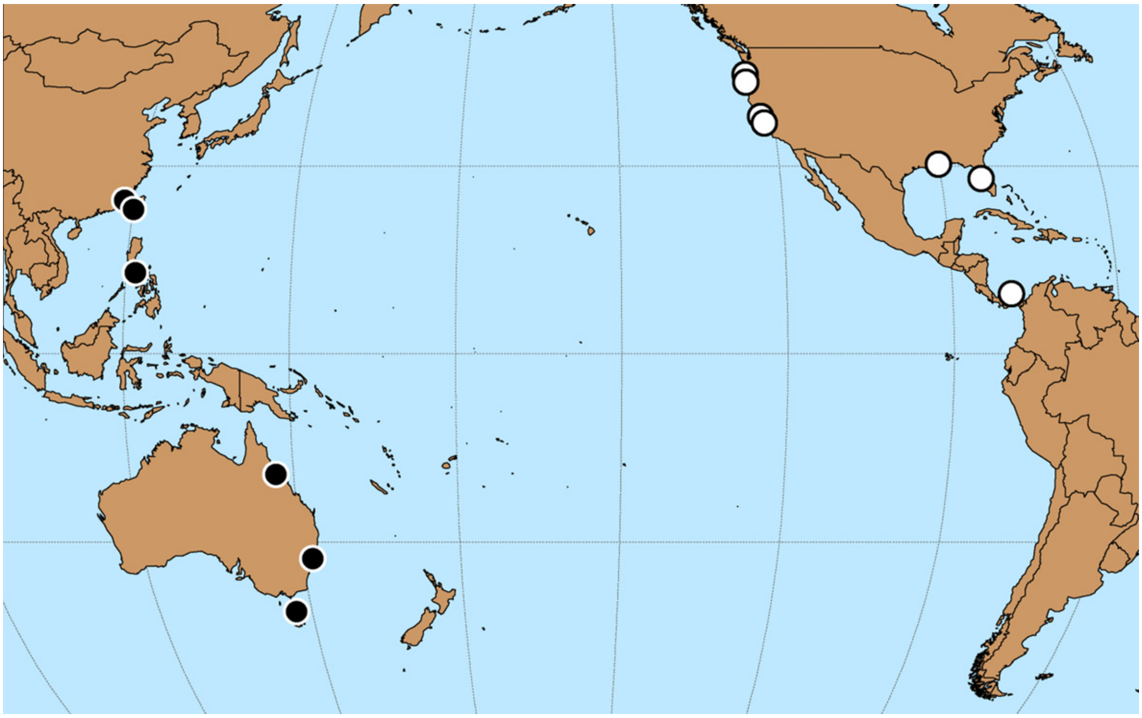

Fig. 5. Global occurrences of boring isopod damage to expanded polystyrene floats. The open circles in North America and Central America represent areas with known damage from non-native sphaeromatid isopods. The closed circles in Asia and Australia denote areas damaged by native populations. See Table 2 for details.

Table 2
Locations where boring sphaeromatid isopods have attacked expanded polystyrene floats.

Location	Date	Species	Invasion status	Substratum	Reference
Yaquina Bay, Oregon	2007	*Sphaeroma quoianum*	Non-native	Floats, flotsam	This paper
Coos Bay, Oregon	1995	*Sphaeroma quoianum*	Non-native	Floats, flotsam	Cohen and Carlton (1995)
San Francisco Bay, California	1966	*Sphaeroma quoianum*	Non-native	Floats, flotsam	Rotramel (1975); per comm.
Elkhorn Slough, California	1998	*Sphaeroma quoianum*	Non-native	Floats, flotsam	Wasson, per comm.
Throughout southwest Florida	1978	*Sphaeroma terebrans*	Non-native	Floats, flotsam	Estevez (1978), per comm
Lake Pontchartrain, Louisiana	2004	*Sphaeroma terebrans*	Non-native	Flotsam	Wilkinson (2004)
Colon, Panama	2012	*Sphaeroma terebrans*	Non-native	Flotsam	This paper
Kinmen Island, Taiwan	2010	*Sphaeroma terebrans*	Native	Flotsam	This paper
Budai township, Taiwan	2010	*Sphaeroma terebrans*	Native	Flotsam	This paper
Tainan, Taiwan	2010	*Sphaeroma terebrans*	Native	Floats, flotsam	This paper
Tamar river, Tasmania	2006	*Sphaeroma quoianum*	Native	Flotsam	Davidson et al. (2008)
Port Stephens, Australia	1986	*Sphaeroma quoianum, Sphaeroma terebrans, Ptyosphaera alata*	Native	Floats	Cookson et al. (1986)
Townsville Australia[a]	1973	*Sphaeroma triste*	Native	Floats	Harrison and Holdich (1984)
Philippines[b]	1986	*Sphaeroma terebrans, Sphaeroma triste*	Native	Floats	Angell (1986)

[a] Harrison and Holdich (1984) noted *Sphaeroma triste* in polystyrene blocks (in 1973) affixed beside a dock in Townsville, Australia but is unclear if the dock used these blocks as floats.
[b] Angell (1986) reports the necessity of protecting expanded polystyrene floats used in oyster culture facilities in the Philippines from borers; while not explicitly stated, these borers are likely *S. terebrans* or *S. triste*.

et al., 2011). These particles were similar in size to numerous species of zooplankton and some phytoplankton (Hansen et al., 1994; Sprules et al., 1998) and thus may be confused for planktonic food. Microplastics are ingested by species in a variety of trophic levels, habitats, and feeding modes. They have been ingested by detritivorous amphipods (Thompson et al., 2004); deposit feeding echinoderms (Graham and Thompson, 2009) and polychaetes (Thompson et al., 2004); filter feeding mussels (Browne et al., 2008), crustaceans (Thompson et al., 2004), and echinoderms (Graham and Thompson, 2009); omnivorous lobsters (Murray and Cowie, 2011); and small planktivorous fish (Boerger et al., 2010; Davison and Asch, 2011). Larger predators such as birds (Laist, 1997), turtles (Laist, 1997), numerous species of fish (Carpenter et al., 1972; Kartar et al., 1976; Laist, 1997) and mammals (Ericsson and Burton, 2003) were also found with microplastics inside their guts. Since isopods damage the floats used in aquaculture facilities, the microplastic pollution created may even become ingested by the cultured species (for example, oysters) and thus may be transferred to humans.

There are three primary effects of microplastics to marine life including facilitating the spread of non-native or toxic species and both physical and toxicological effects when ingested. Microplastics may facilitate the spread of non-native species (Barnes, 2002; Gregory, 2009) by providing a surface to which those organisms can attach and subsequently floating to a new area. Numerous non-native taxa have been found on plastics including sponges, hydroids, bryozoans, mollusks, isopods, barnacles, polychaetes (Barnes, 2002; Gregory, 2009) and toxic microalgae (Masó et al., 2003). Even microplastics may be a viable vector; plastics similar in size to the current study have been found transporting non-native bryozoans (Barnes, 2002; Gregory, 2009). The high surface area of these microplastics and high abundances created through burrowing may provide additional opportunities for small non-native taxa to colonize and disperse to new areas.

When ingested, microplastics can also accumulate in some organisms (Browne et al., 2008; Murray and Cowie, 2011), which may possibly lead to physical effects. The accumulation of plastics may lead to intestinal obstructions (Carpenter et al., 1972) and stomach ulcers (as with birds, Pettit et al., 1981). It also may cause false indication of satiation, hence reduced growth and perhaps fitness (Connors and Smith, 1982; Ryan, 1988). Researchers have found negative correlations between plastic load and body mass (Ryan, 1987; Spear et al., 1995) and possibly the amount of fatty deposits in seabirds (Connors and Smith, 1982). However, it is unclear if microplastics can also cause similar negative physical effects to biota; this question remains an important gap that needs to be addressed (Cole et al., 2011). Browne et al. (2008) did not find a significant short-term biological effect of the ingestion of microplastic in the mussel *Mytilus edulis*; however, they caution additional longer-term studies with an array of different polymers and organisms are necessary.

Microplastics are chemically inert (Andrady, 2011; Teuten et al., 2009), yet may become toxic due to degradation or the accumulation of toxins from the ambient environment. When the plastics degrade, they release toxic additives including phthalates, organotin, and nonylphenol (Mato et al., 2001; Teuten et al., 2009; Zitko, 1993). Other toxins, such as persistent organic pollutants, have a higher affinity for plastics than ambient seawater and accumulate in very high concentrations (Mato et al., 2001; Teuten et al., 2007) and may be absorbed into marine fauna (Ryan et al., 1988; Teuten et al., 2007; Thompson, unpublished, as cited in Teuten et al., 2009).

These persistent organic pollutants including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAH's), chlorinated phenols, organochlorine pesticides (DDT and DDE) and Bisphenol-A (BPA) are of particular concern since they are endocrine disruptors and carcinogenic (Walker et al., 2006). Furthermore, heavy metals (Cadmium and Lead) can also accumulate in microplastics (Ashton et al., 2010). Since the microplastics created by isopods are small, irregular, and have a high perimeter to area ratio (and likely a high surface area to volume ratio), it seems likely they would accumulate toxins more rapidly than larger spherical plastic particles and pellets.

4.4. Polystyrene float type prevents colonization by a non-native boring isopod

Isopods did not burrow into the XPS foam treatments during the lab experiment, which suggests this foam type may prevent isopod colonization and burrowing in the field. These lab results are consistent with observations from the field. The XPS floats or flotsam encountered during surveys were never burrowed by isopods (per. obs.). The XPS foam is noticeably harder than EPS foam and it is likely this substratum is too hard for boring. In contrast, EPS foam, such as the type used in many floating docks, was burrowed more frequently and burrowed deeper than the other treatments. The damaged encapsulated EPS float mimics also exhibited lower colonization rates, burrow use, and shorter burrows than the EPS floats, although the results were not statistically different. While these results suggest a thin encapsulation material may inhibit boring to some degree, I recommend using a hardened polyethylene shell around an XPS foam core to prevent damage from borers and debris and degradation from the ambient seawater. This laboratory experiment, combined with field and lab observations, suggests that XPS is resistant to isopod damage and thus may be a viable option to reduce the impacts of burrowing by *S. quoianum* and other boring isopods.

5. Conclusions

The destruction of expanded polystyrene floats used in floating docks and aquaculture facilities by boring isopods can be extensive. Burrowing by dense colonies of isopods degrades floats, reducing their longevity and function. Burrowing also releases millions of microplastic particles into the marine environment. These particles are similar in morphology to other microplastic particles (Carpenter et al., 1972; Gregory, 1996) and may have detrimental effects to marine organisms. These negative effects, however, may be prevented or mitigated by using extruded polystyrene floats and/or a thick rigid encapsulation material under docks and facilities.

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