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Fishing gear and other anthropogenic debris harbour invasive species

1.1 Abstract

Records of non-indigenous and invasive species in published scientific literature were found in all marine regions, except the Southern Ocean, and more often than would be expected in a comparable marine community. Comparisons were enabled by the organisms associated with AMD database of scientific literature published between 1992 and 2019 combined with taxonomic and invasion history data available on the World Register of Marine Species. Across the nine animal phyla recorded in the OAAMD, the proportion of formally designated invasive species in communities on anthropogenic marine debris (AMD) was over 60 times higher than in the overall marine community. Invasive species were found outside of their specialist-delineated native marine regions in over 85% of records. Of these, 80 records represented novel findings in marine regions outside of their known range. Records of invasive species were also significantly more common within 150km of an urban coastal area. Although the type of AMD was often not reported at the level of an individual

organism by the studies synthesised, available data did suggest that NIS may more often be found on structurally complex debris items like fishing gear and synthetic fabrics than on flat or smooth plastics, metal, and natural materials.

1.2 Introduction

Driftwood, kelp mats, and other types of naturally occurring debris floating at the ocean's surface support diverse communities of organisms adapted to the specific habitat conditions they provide [**thielRaftingBenthicMacrofauna2003**]. The long history of association between these communities and natural floating debris has moulded geographic distributions of these organisms along the paths of surface currents driven by prevailing winds [**luizSeafarersCastawaysEcological2015**, **pfallerHitchhikingHighSeas2019**]. Rafting, the process in which species are transported by floating debris, has also been shown to occur aboard the mass of anthropogenic marine debris (AMD) now floating alongside this natural mixture [**barnesRemoteIslandsReveal2005**, **gilOceanicBarnaclesAct2016**, **mirallesAlertCallingPo**

Since AMD presents a large and increasing amount [**koelmansAllNotLost2017**, **lebretonEvidenceThatGreat2018**] of solid surface area in the top layer of the ocean, it may also present a large and increasing amount of habitat capable of transporting associated organisms. This implication of increasing plastic production and pollution was hypothesised early on [**winstonDriftPlasticExpanding1982**], as observational studies continued to find beach debris fouled frequently by species noted to be similar to those found on **Sargassum sp.** [**gregoryHazardsPersistentMarine1991**] and on the beaches of extremely remote islands [**ryanAccumulationStrandedPlastic1988**]. These early papers proposed that pristine coastlines, previously buffered from human impacts by sheer distance, would become vulnerable to anthropogenic disturbance and the introduction of harmful species both marine and terrestrial.

The next thirty years of research show that the scope of impacts from rafting aboard AMD is potentially far more complex and pervasive. Fouling organisms, multicellular plants and animals which grow attached to the surface of an object immersed in water, have been found on AMD in every marine region [**kiesslingMarineLitterHabitat2015**, **alvespovoaFoulingOrganismsMarine2021**] on beaches both remote [**rechTravellingLightFouling2018**] and highly urbanised [**mirallesAlertCallingPort2018**]. In oceans and seas, this fouling community has been shown to attract and support communities of mobile predators and grazers [**tutmanFloatingMarineLitter2017**, **whitneySurfaceSlicksAre2021**]. Among these associated organisms are those with histories of causing harm when established outside of their native range [**mirallesAlertCallingPort2018**, **shabaniAssemblageEncr**
Even at the microbial level, AMD has been shown to carry pathogens harmful to humans and wildlife [**audrezetBiosecurityImplicationsDrifting2021**, **virsekMicroplasticsVectorTransport2017**]. The distances travelled by AMD and these problematic species are much further than any recorded aboard natural substrate [**simkaninExploringPotentialEstablishment2019**].

1.2.1 Natural versus artificial

This abundance of material and its capacity for long-distance dispersal of hitch-hikers distinguish AMD from historical modes of oceanic rafting. Natural materials are capable of facilitating long-distance dispersal [**talaLongtermPersistenceFloating2019**]. However, their abundance at the ocean's surface are often tied to natural phenomena like seasons or storms [**hinojosaTemporalSpatialDistribution2011**]. This abundance, as well as how far they can travel, may be also be limited by degradation caused by many physical, chemical, and biological processes [**rothauslerMercyWindsSeasonal2021**

In contrast, common sources of AMD [**koelmansAllNotLost2017**], such as riverine and stormwater outflows, typically discharge some volume of material to the ocean year-round. Products manufactured from plastics, wood, rubber, and other artificial or enhanced materials are, often deliberately, resistant to physical and chemical degradation and there are few known organisms capable of metabolising or otherwise breaking them down [**gewertPathwaysDegradationPlastic2015**]. This may be why AMD has been observed to arrive and persist at times, in places, and in quantities in which natural debris would be highly unlikely [**ruiz-orejonQuarterlyVariabilityFloati** **guerrero-meseguerSpatioTemporalVariabilityAnthropogenic2020**, **jaskolskiTrashArcticE**

1.2.2 Dispersal potential

This could mean that organisms with the capacity to use AMD as habitat are more able to shift the boundaries of their known ranges and disperse over very long distances. Abundant substrates, particularly around urban areas [**citekey**] or after natural disasters [**citekey**], could offer these organisms more chances and at more optimal times of year to establish populations in new, previously inaccessible, areas. This could help mitigate losses to marine biodiversity as suitable habitats shift around with climate change. AMD associated organisms may be more likely to randomly find their new habitable range than those not able to utilize it.

However, this same process may also increase the likelihood that invasive species spread to areas beyond the site of their initial incursion (secondary invasion) or to regions far beyond the reach of natural sources of population control. When the Tohuku-Oki earthquake caused a tsunami that flooded the area surrounding

Fukushima Daiichi, Japan in 2011, entire communities of marine life were transported across the North Pacific on thousands of items ranging from household litter to entire piers [**Carlton2017**]. No natural substrate, like driftwood, has even been documented making that same trip [**citekey**]. These organisms, separated by tens of thousands of kilometers and hundreds of thousands of years of evolution, were only able to make the trans-Pacific journey because of AMD. Dozens of them were identified as species with histories of invasion [**citekey**].

Numerous other studies have documented shorter-distance travel aboard debris to new locations just outside of a species known range [**citekey**, **citekey**]. Through short hops from ports areas, seen in **Miralles2014**, AMD has shown its potential to expand the spatial extent of incursions in these types of invasion hotspots. The inherently random, omnipresent, and indirect character of AMD which would make these halos difficult to search or monitor for this effect also makes it difficult to implicate it as the original source of an introduction with any certainty. However, it had been documented as a component in over a dozen invasive species incursions in literature published prior to March 2020 [**garcia-gomezPlasticVectorDispersion2021**]. Through an indirect process of elimination, AMD has also been suggested as the only reasonable pathway for the spread of the **Mytilus** species complex, which contains known invasive species, to a remote island in the Arctic circle with little vessel traffic or natural debris deposition [**kotwickiReappearanceMytilusSpp2021**].

1.2.3 AMD as a pathway

In the context of marine biosecurity, introduction pathway refers to a way that humans transport species around oceans and seas. **Vectors** are the common trajectories taken by those pathways, such as high-traffic commercial shipping lanes. Some species transported by pathways along vectors are designated by regulatory or management bodies as **invasive species**. This designation is generally given once it has been demonstrated that the species causes significant harm to human and/or natural systems. With enough research and information, invasive species can be associated with a specific pathway, or set of pathways, known to more often facilitate their dispersal. AMD could be considered a pathway for each of the hundreds of species found to use it as habitat [**citekey**].

A 2021 meta-analysis estimated that harms related to aquatic invasive species, combining both freshwater and marine environments, cost the global economy a total of 23 million USD in 2020 alone [**Cuthbert2021**]. These costs may arise directly from mitigation efforts and lost revenues in fisheries [**Schwoerer2019**] or damage to infrastructure [**Park1999**], among other economic impacts. Beyond monetary costs, invasive species can change how ecosystems function, altering the composition of native species [**Jackson2017**] and reducing the services those ecosystems provide to human communities [**Katsanevakis2014**].

Characterisation of an introduction pathway and its vectors can inform strategies used to mitigate the risks it can pose [**citekey**]. When incorporated into management plans including early-detection and rapid response capabilities, they comprise contemporary biosecurity best-practices for preventing and efficiently responding to incursions of NIS [**Hewitt2007**]. Recent efforts to describe AMD as a pathway have collected lists of species, both micro-organisms [**citekey**] and those visible to the naked eye [**citekey**], and contrasted it with other pathways [**garcia-gomezPlasticVectorDispersion2021**]. More general research into AMD offers insights into its sources, vectors, and sinks [**citekey**] and provides predictions for how these may change in the future [**citekey**].

1.2.4 Assessing the potential of AMD

To further understanding of AMD as a pathway, this study combined a 2021 database of published records of organisms associated with anthropogenic marine debris (OAAMD) [**McMains2022**] with the World Register of Introduced Marine Species (WRiMS) [**Rius2020**], to compare the frequency of invasive species found on AMD with their frequency in the rest of the marine environment. This combination of sources also enabled the assessment of spatial and methodological patterns specifically in records of invasive species on AMD. Combined with one of the most comprehensive lists of invasive species found on AMD as of 2021, this investigation aimed to delineate which species use this pathway and characterise patterns in its vectors.

1.2.5 Material types

Not all substrates categorised as AMD provide the same type of habitat and certain substrates are more associated with certain patterns of movement through the ocean's surface layer. These distinctions often do not fall along the same lines as those useful when sorting debris found on the beach. As such, the way AMD is categorised for the purposes of this study is different than in many others. The categorisation described below also accomodates reporting gaps in the literature and groups substrates into categories broad enough to be statistically useful.

Fishing gear

Nylon fishing nets, expanded polystyrene foam buoys, and synthetic rope were grouped alongside other diverse materials originating from fishing and aquaculture activities. Though they are made from a variety of polymers, with different chemical additives, and offer diverse surface properties to fouling organisms, this category shares two definitive characteristics. First, almost all of these materials will be discharged into the marine environment with an existing marine biofilm. This primes their surfaces for easy attachment of juvenile macro-organisms and increases the likelihood that they already have adult fouling organisms attached. Second, is that they are designed to be used outdoors in sunny, wet, and salty conditions. Previous studies have shown that these characteristics can or do manifest as distinct biological communities [**citekey**, **citekey**].

Megastructure

Large objects comprised of multiple named or unnamed materials were grouped as megastructures. These objects are likely to provide several different types of habitat, enabling niche partitioning for greater diversity. As a whole object, their tendency to resist degradation for long periods of time may enable these diverse communities to travel longer distances and develop into more complex community structures [**citekey**]. There may also be enough reproductive adults to sustain stable populations over long journeys [**citekey**]. This makes them distinct from smaller objects which may not have sufficient space to do so.

Plastic

Simple objects resembling plastic, or familiar plastic products, were often simply labelled plastic in their source paper. Where spetroscopy was used to accurately identify the polymer, this was rarely reported in association with the organism itself. This methodological quirk is mitigated by the fact that polymer type has been shown to have far less effect on the associated community than environmental factors [**citekey**], if there is even a detectable difference at all between them [**garcia-gomezPlasticVectorDispersion2021**]. These factors, like season and salinity, and how they act on the object due to aspects of its structure, such as buoyancy or shape, have more of an affect than polymer type but are no more feasible to include in any analysis. Differentiating between foamed and un-foamed plastic may be useful in future studies [**citekey**], but there was not enough data to do so here.

Microplastics, as categorised by the source paper, were excluded from analyses relating to the associated biological community. These tiny plastics were often collected and processed using different methods than larger plastics. Their associated community was more often described in bulk and using molecular techniques, whose outputs require a different set of assumptions around taxonomic certainty and potential contamination. Therefore, plastic refers only to items characterised as macroplastic in its source paper and does not differentiate between polymer types.

Glass and ceramic

Glass bottles and ceramic fouling plates, which comprise the majority of this group, have both been shown to follow similar successional patterns [**citekey**] due to their low surface energy. They present a relatively difficult surface for establishment when first introduced to a marine environment and are resistant to the surface pitting that facilitates settlement by macro-organisms. However, they both are fragile to impact and are prone to sinking if damaged. They are also far less likely than plastics to adsorb and absorb chemicals that may harm the associated community.

Fabrics

There was no reporting of fabric type in any of the studies in the OAAMD. However, common natural fibres are less water resistant [**citekey**] and can therefore be assumed to be relatively rare at the oceans surface. Polyester and other artificial fibres, including heavily modified natural fibres like modal, were therefore combined into one group along with the potential inclusion of natural fibres which had not yet become too waterlogged to float. Despite the fibre, all fabric substrates can be assumed to provide ample gaps for the attachment of organisms and little resistance to folding or turning in ways expose attached organisms to a variety of environments and stressors.

Metal

Metals were never reported to their alloy or specific metallic content and were comparatively rare. Data availability determined this category. Different metals and their characteristic chemical interaction with the marine environment and organisms would suggest that separating them might improve understanding of material specific patterns. However, it can be reasonably assumed that metals provide a distinct habitat to that provided by the other categories. Including them in the analysis was seen to provide a useful basis for further targeted exploration because, despite their rarity in the OAAMD, they are often found in beach clean-ups [**citekey**].

Other

This group contains records of rubber, paint chips, and objects described to their purpose where they could not be placed in any other category. Their dissimilarity means this tactic offers little information value each sub-type. Instead, it can be seen as a background catch-all for artificial substrates, suggesting an uncertain average for these materials.

Unknown

In some cases there was no available information on the object that the organism was found on. In these cases, where the study focussed entirely on AMD, it could only be assumed that the object was artificial or manufactured. This was kept separate from the “Other” category because almost all of the records in this group came from the Japanese Tsunami Marine Debris database. The source was considered to separate these two categories into distinct populations.

Natural

Kelp, driftwood, and seagrasses were sometimes mentioned in studies otherwise focussed on AMD. Each of these materials is known to have a different associated biological community, but there were not enough records to separate them out individually and still maintain comparable statistical inference to what was available for the other categories. Like the other category, this grouping is most useful to provide an uncertain average across these materials and for comparison to AMD.

1.3 Methods

This study combines information from four databases compiled fully cited peer-reviewed or specialist-verified records:

- *OAAMD*: Organisms associated with anthropogenic marine debris [**McMains2022**] synthesised over 20 years of published research in life- and materials-science to provide a collated database of recorded associations of organisms with floating and immersed anthropogenic marine debris and their locations;
- *WRiMS*: The World Register of Introduced Marine Species [**Rius2020**] combined contemporary lists of species known to biosecurity agencies as invasive, managed, or potentially concerning from 64 countries (Supplementary data);

- *WoRMS*: The World Register of Marine Species [**WoRMSEditorialBoard2020**] provided standardised nomenclature for each organism and was utilised as the most comprehensive and robust available reference of marine species known to science;
- *Marineregions.org* [**citekey**]: Compiled geospatial databases of marine regions from multiple gazettes into one source with stable resource identifiers accessible from a public API such that each spatial coordinate pair in the OAAMD could be associated with a Marine Ecoregion of the World (MEOW) [**citekey**].

1.3.1 Data compilation

The OAAMD provided the lowest level records for which the rest of the information was queried and added. WRiMS was used to indicate whether each recorded organism had a history of invasion. WoRMS provided the full taxonomic classification for each record according to general scientific consensus as of January 2021. Its functionality enabled older binomial names and classifications to be updated for the analysis and summary tables in this chapter. Marine ecoregions for each spatial coordinate pair in the OAAMD were pulled from the Marineregions.org API in May 2021. The same API was also used to convert countries with invasive species lists in WRiMS to Marine Ecoregions.

Lists of invasive species in WRiMS were labelled by the country or managed marine region that had designated the species as invasive, managed, or of concern. These three broad categories were lumped into one label "NIS" for this analysis because there were very few records of organisms in the OAAMD which were designated using the latter two categories (Table (code snip)). NIS was chosen to represent the three to accommodate the fact that not all of the species were fully listed as invasive and certain analyses did not account for whether the species was found in a region that had listed it.

Known contemporary geographic distributions for each species found in the OAAMD and listed as an NIS in WRiMS were pulled from specialist-validated sources in April 2021. These sources, in order of preference were: - the Smithsonian's NEMESIS database [Fofonoff2021]; - WoRMS [WoRMSEditorialBoard2020]; - CABI Invasive Species Compendium [**CABI2021**]; - and the Global Invasive Species Database [**GISD2021**].

These sources were supplemented, in some cases, by published scientific articles or theses (Supplemental data). Where active scientific debate or uncertainty about an organism's native range was ongoing in 2020, the organism was listed as having no native range and excluded from analyses focused on regional patterns. These distributions were described using Marine Ecoregions of the World [**citekey**].

1.3.2 Material type

For the purposes of this analysis, material type was summarised into several broad categories based on the more varied assortment reported in the OAAMD. The categories, described earlier in this chapter, are again summarised in Table 1.1. They represent an attempt to best group within data availability and factors known to influence fouling patterns.

1.3.3 Analysis

Statistical analysis and visualisations for this paper were completed in the R Statistical Computing environment (R Core Team, 2018) and tested the following hypotheses:

Table 1.1: Material type designations used to classify the broader range of materials found in the OAAMD to provide adequate sample sizes in the following statistical analyses.

Material	Definition
Plastic	All petroleum-derived synthetic materials not noted as fishing gear.
Fishing gear	Materials that originated as the result of fishing or aquaculture activity.
Megastructure	Complex, large structures composed of multiple potential materials.
Fabric	All fabrics as described in the source literature (assumed synthetic).
Glass or ceramic	Smooth and rigid non-petroleum derived artificial substrates.
Metal	All materials identified as metal or a type of metal.
Other	Broad, diverse category of materials each with a small number of records.
Unknown	Used where material type was unreported in the source.

- H1: The percentage of NIS within the community recorded on AMD is not significantly higher than in the background marine community;
- H2: The percentage of NIS within the community recorded on AMD is not significantly higher on debris within 150km of coastal urban area than outside of this radius;
- H3: NIS are not found within the community on AMD more frequently in marine regions directly adjacent to or within the native range for the species.

H1: Prevalence of invasive species in the recorded AMD community

The community recorded on AMD is determined by physical aspects of the environment, the biology of each organism, interactions between organisms, and biases inherent to scientific effort and publication. These may combine to impact how many species on a debris item are designated as invasive species (called NIS in this analysis). The aim of this test was to determine whether the unique characteristics of AMD increase the prevalence of NIS above that found in the background marine community.

Randomly simulated communities of animals from nine phyla were created from the two separate lists of species: OAAMD and WoRMS. The percent of this community comprised of NIS was calculated and used to generate two separate frequency distributions. These were then compared using a chi-square test. This analysis did not account for regional factors, unavailable for the species not listed as NIS, and instead investigated overall global trends.

Random, unweighted sampling without replacement was performed using the random number generator included as a basic function in the R programming language [**citekey**]. The number of samples in each run was selected randomly from a normal distribution with the same mean, minimum, and maximum as species richness within studies in the OAAMD (minimum 6, mean = 42, max = 89). 10,000 communities were randomly generated in this way from each list of species. The percent of the total community which was identified as an NIS was then calculated.

This process was repeated 10,000 times for each of the two datasets, resulting in 20,000 calculations of the percent of NIS in the simulated community. An ANOVA based on a logit-link linear model [**citekey**] was used to test whether the distribution of percent NIS was significantly different between communities simulated from the OAAMD and WoRMS datasets. A logit model was selected because its assumptions align with the derived probabilities calculated during the simulations [**citekey**].

H1a: Increased likelihood of recording listed invasive species

This process was performed again with the addition of a weighting value applied to the selection of species listed as NIS. The weighting value increased the likelihood that an NIS would be selected at random, relative to non-NIS species, from the list of species found in WoRMS. Weighting values were set at each of the numbers between 5 and 100 to generate a logit-link linear model of the relationship between likelihood of selecting an NIS and the resulting proportion of the simulated community that NIS represent. These values were selected to incorporate the high variability in percent NIS seen in the unweighted model and anchored around the overall ratio of NIS within the AMD and background marine communities compared (approximately 60 non-NIS for each 1 NIS). A statistically similar proportion of NIS to that found on artificial debris was inferred to be found where confidence intervals (2.5% and 97.5%) overlapped the mean proportion calculated from the 10,000 simulations on the AMD community.

H2: Urban centres influence on prevalence of listed invasive species

Geographic coordinates for each record, provided within the OAAMD, allowed for the identification of records found within a 150km radius of the centre point of a named settlement with a population over 50,000 as of 2018 [**citekey**]. Records within this radius were considered urban, according to the definition of large towns and urban centres provided by the Australian Bureau of Statistics [**citekey**] A chi-squared analysis [**citekey**] was used to test whether the number of records of listed invasive species was significantly higher than non-listed species on AMD within this radius. The 150km distance was selected as it was a natural break [**citekey**] in the data that provided adequate sample sizes of records on both sides of its boundary. This likely incorporates reasonable travel times of vessels (collection at sea) and along roads (beach collection) for researchers on day trips from the urban regions they are often based in. Urban effects from common activities may, presumably, follow similar patterns based on accessibility.

H3: Connectivity between the native range of NIS on debris and where it was found

The scientifically established ranges of each NIS were compared to the regions where the organisms were recorded in the OAAMD database [**citekey**]. This allowed records of NIS found within their native ranges to be excluded from the connectivity analysis. The "distance" between each remaining record and its nearest native or introduced range was then calculated as the fewest number of regions it would have "passed through" to travel between the two using a breath first algorithm in the iGraph implementation in R [**citekey**].

Each record was assumed to have come from the nearest native region for that taxa. When distance ties occurred, both regions were assumed to have been the source. Secondary introductions, in which a species is transferred from its introduced range into another new region, and more complicated journeys across multiple regions were not included in the assumptions of this model. Though likely scenarios, the dataset used includes numerous sources of variability and error that would not support such a complex model.

Connection weight was quantified as the number of NIS records in region "A" likely originating from region "B". Regions were grouped using the algorithm developed by **Brandes1997** which maximises the strength of the connections within the group and minimises connections to nodes outside of the group. This analysis and the creation of visualisations were performed in the R implementation of iGraph [**citekey**] using tidygraph [**citekey**] and ggraph [**citekey**]. Records from Japanese tsunami marine debris were excluded from this portion to achieve more balanced sample sizes.

1.4 Results

Of the 4235 recorded organisms in the complete database of OAAMD, 132 belonged to species listed as an invasive, managed, or concerning species in the World Register of Invasive Marine Species [**Rius2020**] (Table (code snip), Supplementary material). Throughout the recorded time-period (1990-2019), the ratio of unique NIS to unique taxa stayed steady at around 5% (Figure 1). Records were concentrated in the NE

Pacific Ocean (n = (code snip)), due to the thorough study of debris related to the Japanese tsunami (Carlton et al., 2017). Outside of this study, the next most frequent regions were European territorial waters in the NE Atlantic Ocean (n = (code snip)) and Mediterranean Sea (n = (code snip)). The listed invasive species most frequently found are globally wide-spread and known to have broad environmental tolerances: Mytilus galloprovincialis [**citekey**] (n = (code snip)), Megabalanus rosa [**citekey**] (n = (code snip)), and Magallana gigas [**citekey**] (n = (code snip)). Listed taxa were most common on fishing gear (n = (code snip)) and megastructures (n = (code snip)), the latter primarily associated with Japanese tsunami debris.

```
test <- wrims_db %>%
  select(accepted_name_usage, source, country_code, invasiveness, locality) %>%
  mutate(invasiveness = ifelse(invasiveness %in% c("Invasive", "Of Concern", "Manag
                               invasiveness,
                               "Other"),
         country_code = str_replace_all(country_code, "England|Scotland", "GB"),
         country_code = str_replace_all(country_code, "Taiwan", "TW"),
         continent = countrycode::countrycode(country_code,
                                              destination = 'continent',
                                              origin = 'genc2c'),
         source = str_sub(source, 1, 6),
         continent = case_when(!is.na(continent) ~ continent,
                               source == "Katsan" ~ "Europe",
                               source == "DAISIE" ~ "Europe",
                               source == "Molnar" ~ "Europe")
         ) %>%
```

```
select(-c(source, country_code)) %>%
filter(invasiveness != "Other") %>%
rename(designation = invasiveness)
```

Plastics, the most frequently recorded material harbouring associated organisms (n = (code snip)), showed a comparatively low presence (3%) of listed NIS within its associated community (Figure (code snip)). By contrast, items categorised as fabrics (n = (code snip)), showed a very high percentage of NIS within its community. Out of all records related to fabric, 13% were listed NIS, which was a close third behind fishing gear (20%) and megastructures (16%). Few records of NIS were found on hard surfaces like metal (n = (code snip)) or glass and ceramic (n = (code snip)).

Material type was missing for a high number of records in the OAAMD database overall (n = (code snip)) and almost never recorded at the level of an individual organism, which precluded testing hypotheses about the material preferences of specific listed taxa. Location, however, was recorded for all the studies reporting the biological community on floating artificial substrates. While often not recorded at the level of an individual taxa ((code snip)% of records), most studies recorded location data at the study level on a discrete and delineated area of less than 200 km2.

A general scientific consensus, within the sources listed in the methods, was also available for the native and introduced ranges of all but 6 out of 80 total listed species: 2 listed as invasive (Botryllus schlosseri and Bugula neritina) and 4 listed as a concern (Didemnum perlucidum, Lepas anserifera, Megabalanus rosa, and Tricellaria occidentalis). Their entire known range was categorised as introduced. Based on these established distributions, nearly 80 ((code snip)%) records represented a range expansion of an NIS into a novel marine region (Table 1). Fewer than 15% of listed NIS were found within their native range (n = (code snip)). This pattern only broke for the North Atlantic and Indian Oceans (Figure (code snip)), though these regions were also four of the top five most common native ranges for the organisms found on AMD (Table (code snip)).

For NIS found outside of their native range, over 80% were found in a marine region directly adjacent to their native range (n = (code snip)). Connections between the nearest native marine region and the region in which a debris item carrying an NIS was found showed a similar pattern in a graph analysis. Regions grouped using the leading eigenvector method [**citekey**] formed three groups of stronger species transfer (Figure (code snip)), in which the groups were majority composed of adjacent regions. A notable exception to this was in Group A, where the NW Pacific Ocean showed stronger connections with the North Atlantic Ocean and the Eastern Indian Ocean. Again, these exceptions were the top five most common native regions by species found on AMD (Table (code snip)).

Within regions, there appeared to be a statistically significant increase in the proportion of NIS in studies and on debris items found within 150km of cities of over 50,000 population (t = (code snip), df = (code snip), $p < 0.001$) in a chi-squared test [**citekey**]. The documented AMD community near urban regions was comprised of nearly 15% species listed in WRiMS, compared to just over 10% in communities on AMD found in areas more than 150km from urban areas (Table (code snip)).

Summarised across locations and materials, the percent of NIS among the community of organisms on floating synthetic materials ((code snip)%) was shown to be sharply elevated above that in the comparable background marine community ((code snip)%) across the nine most common animal phyla. Communities randomly assembled from all taxonomically registered species in these nine phyla, representing the background marine community, showed significantly different (add test statistic, p < 0.001) proportions of NIS compared to communities randomly assembled from only those species found on AMD according to a logit-link ANOVA [**citekey**]. Across 10,000 simulations, the randomly generated community of AMD showed a mean proportion of NIS equal to 12.3% (sd = 5.0%), compared to (code snip)% (sd = 1.0%) background (Figure 5). A background marine community that was statistically similar to that found on AMD could be generated using weights between 39 and 81, according to the confidence intervals on a logit-link linear model (Figure (code snip)). An identical proportion of NIS was generated when they were 64 times more likely to be selected.

1.5 Discussion

This analysis demonstrates that there is a statistically significant relationship between artificial substrates floating in the world's oceans and invasive species. Characterisation of AMD as an introduction pathway appear to have implicitly assumed this relationship [**citekey**], but until now it had remained untested. This relationship has also remained relatively stable, with around 5% of the organisms identified belonging to an invasive species, since the first records of listed taxa on anthropogenic debris to appear in the scientific literature in 1994 (Figure 1). Starting in 1997 with the first published identifications of an invasive species on AMD, and throughout the topical research boom beginning in the early 2010's, this represents nearly 30-year of stability in the overall ratio of NIS by species richness.

1.5.1 External factors influencing prevalence

It was not possible to determine from the available data whether the cause of this increased presence of NIS was biological or methodological. Biologically, this relationship may arise from selection pressures inherent to synthetic materials floating at the surface of the ocean. Metholodology could influence which organisms are detected and identified to species level and filter which are reported in published literature.

On the first count, AMD may differ from common types of natural debris in ways that make it more suitable to the types of organisms simultaneously more likely to be listed as NIS. The surface of plastic alone could have a large influence on the types of organisms likely to be found on it. Its high surface energy, perceptible in its generally slick texture, has been shown to make settlement and maintenance of connections more difficult for fouling organisms [**Andrady2015**]. Organisms with an existing capacity for attaching firmly to a variety of surfaces may, therefore, be more succesful in establishing and competing for limited space on plastic substates. This capacity could be broadly advantageous by allowing the organism to use a wider range of habitats. Habitat generalism, like this, has been shown to be correlated with invasion history [**citekey**].

Capacity for attaching to smooth, hard substrates may also relate back to the influence of methdology. This description is also true of other pathways with long and well-studied histories of facilitating the transport of invasive species. Ship hulls and anthropogenic structures in urbanised marine environments also tend to have high surface energy. Species that associate with them will likely have had more time and chances to cause harm in places where people would notice it. Designation as an invasive species requires this [**citekey**].

It was also common within the OAAMD for the community to be reported as a value add within tangential studies, particularly studies related to measuring the volume or mass of debris itself. In these cases, it is unlikely that the entire AMD associated community was rigorously catalogued. Increased familiarity with NIS, and external incentives to identify and publish about them, may have increased the frequency at which NIS were reported relative to other taxa in these studies. Misidentifications as NIS may also have occurred in regions with morphologically similar native species due to the non-specialist taxonomic identification methods used almost exclusively in these types of studies.

No component of any of these factors was explored in this analysis. When compared directly in other studies with appropriate data, there is an overall significant and notable difference in the community on natural and anthropogenic marine debris biological cause for the greater number of invasive species found on Both field and lab studies have shown that differences such as these manifest as significantly different communities on natural and artificial marine debris [Dussud2018; **Muthukrishnan2018**; **Oberbeckmann2018**]. Comparisons of methology have also resulted in different communities, when compared directly for anthropogenic substrates [**citekey**].

The influence of human biases and knowledge gaps in designating what is, and is not, an invasive species is also supported by the apparent overlap of species found on AMD and identified from ship hulls [**citekey**]. Most of the NIS found on AMD are known to foul the hulls of ships, marine infrastructure, and fishing and aquaculture equipment. Some are so successful at this that their native range is difficult to delineate due to the long history and persistence of their association, in particular, with vessel hulls, such as the **Watersipora subtorquata** species complex [**citekey**]. Other notable associations with artificial surfaces, such as coastal infrastructure and aquaculture equipment, are shown in the cases of ... (Chad chime in?).

1.5.2 Secondary introductions

Regardless of cause, the elevated proportion of the community on AMD composed of invasive species may justify the recent increased attention to its function as an introduction pathway [**citekey**]. The discussed association between invasive species on AMD and urban areas, with its potential to facilitate secondary introductions, is also supported by the results of this analysis. Invasive species were recorded significantly more often near urban areas, even accounting for the larger number of studies focussed there. Not accounted for was the known increased prevalence of invasive species near urban regions overall [**citekey**].

Human activities cause both introductions of invasive species and the abundance of AMD in the marine environment. Their co-occurence is not particularly notable. However, their overlap, combined with the higher percent of the community comprised of invasive species on urban AMD, may have an amplifying effect. Abundant AMD could increase the chance that an invasive species passively spreads to new sites beyond the expected bounds of an initial incursion. Secondary introductions can significantly increase the difficulty of eliminating exotic species [**citekey**]. This is particularly true when they occur outside of known high-risk areas with frequent monitoring, like ports [**citekey**]. The AMD pathway may require expanding the spatial extent of areas with a significant risk of invasive species introductions to account for these short-hops.

1.5.3 Long-distance transport

Longer trips, such as those seen by Carlton et. al when studying debris items from the Japanese tsunami, might be far more likely during similar extreme events when large debris flows are quickly washed offshore. No other study has looked at this effect, although annual events such as monsoon and hurricane seasons may force debris out to sea in similar quantities. Japanese tsunami debris overall showed (code snip)% NIS among its community, a total of (code snip) taxa, and (code snip)X records of **Mytilus galloprovincialis** [**citekey**], the Mediterranean mussel, across (code snip) objects. Similar extreme events could also cause repeated introductions of genetically diverse and sexually mature organisms in a short time span, thereby sharply increasing the likelihood of successful establishment of an exotic species in a new region [**citekey**].

This differs in both form and function from other modes of long-distance transport of invasive species. Ballast water and hull fouling vectors are spatially discrete and relatively predictable [**citekey**]. They are also harsh environments distinct from the naturally occurring environments that have shaped the evolution of marine species. Hull-foulers must withstand large physical stresses because of the speed at which modern ships can travel [**citekey**]. Organisms in ballast water must be able to survive without sunlight, or the energy captured from it by autotrophic plankton, in water that quickly becomes depleted of oxygen [**citekey**].

Although the substrate of AMD itself is very different from its natural analogue, the environment surrounding it is comparatively quite similar to what organisms may have adapted to on natural wrack or rafting substrates [**citekey**]. AMD travels along similar vectors to natural debris, driven by the same forces, simply in greater quantities and potentially over greater distances [**citekey**]. This may facilitate the long-distance dispersal of organisms previously unable to do so on other pathways.

1.5.4 Conclusion

In either scenario, AMD shows its potential as a pathway for marine organisms to expand outside of their native range, and, potentially, cause ecological and economic harm to coastlines in almost every marine region on Earth. It creates an abundance of habitat suitable for NIS transported through other, more highly regulated, vectors like shipping and aquaculture. Secondary introductions outside of monitored areas via the AMD pathway may require a shift in marine biosecurity protocols and long-distance dispersal aboard AMD presents an entirely novel type of biosecurity threat. This study has established that not only are plastics and other synthetic materials capable of providing habitat to a diverse range of listed pest species (Table (code snip)), but that these species may be far more likely to be found associated with AMD.