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Encrusters, Epibionts, and Other Biota Associated with Pelagic Plastics: A Review of Biogeographical, Environmental, and Conservation Issues

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Introduction

Entanglement, ingestion, and ghost-fishing are well-documented biologically damaging effects of marine debris. Debris may also smother benthic communities on soft and hard bottoms (Parker 1990). For a number of organisms, however, plastic debris provides a positive opportunity, creating new habitats in the form of numerous, semipermanent floating islands, which are driven by winds and currents around the world's oceans. Although these epibiotic assemblages seem to be most common in warm-water regions, biologically encrusted plastic items have already been found at sites ranging from the Subantarctic to the Equator (Gregory et al. 1984; Gregory 1990a, 1990b). This paper focuses on studies by the three authors at sites in the Western Atlantic and the Southern Pacific, with findings of worldwide relevance.

Western Atlantic Drift Plastic Studies: Islands in the Stream

Three studies of drift plastic epibionts were carried out at North Beach in Fort Pierce, Florida (approximately 27° 29′ N, 80° 25′ W). These Florida studies have been supplemented by observations and collections made on the shores of Bermuda in 1978 (Gregory 1983) and in October 1990 (Gregory, unpublished data). Bermuda beaches are also strongly influenced by the Gulf Stream and gyral circulation of the Sargasso Sea.

The Florida study site (Fig. 7.1) is a gently sloping, east-facing barrier island beach, stretching north from the Fort Pierce Inlet along the Atlantic coast of North Hutchinson Island. Inshore currents generally flow southward. The north-flowing Gulf Stream current (as indicated by water color, temperature, and presence of *Sargassum*) is usually encountered between 15 and 20 miles offshore (Worth and Hollinger 1977; Hugh Reichardt, Smithsonian Marine Station, personal communication). Prevailing winds are from the southeast, or, in the late fall and winter, from the northwest (Worth and Hollinger 1977). Material washed up on the beach may include sea grasses, mangrove leaves, and mangrove propagules carried out of the adjacent Indian River Lagoon through Fort Pierce Inlet as well as locally derived recreational debris (e.g., fast-food containers and drink bottles). However, at any time of year (but most frequently in fall and winter) passing storm systems may cause several days of onshore easterly winds, which increase wave action and cast *Sargassum, Physalia,* and other members of the Gulf Stream *Sargassum* community onto the beach, along with large amounts of mostly plastic marine debris.

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FIGURE 7.1. Drift line at North Beach, Fort Pierce, Florida, shows pelagic *Sargassum*, seagrass, and plastic trash.

Florida Study One

The initial Florida study (December 1980) was undertaken as part of a survey of the marine bryozoans of the Indian River area (Winston 1982a). In this first study, plastic items encrusted by bryozoans (Fig. 7.2) were collected along 0.8 km of beach from the Inlet breakwater northward. It was concluded that the bryozoan *Electra tenella*, previously known from natural flotsam such as floating wood and sea beans, was the dominant organism on the trash, and further speculation is that this species might be increasing its abundance and distribution via the increasing amount of plastic entrained in Caribbean and Gulf Stream currents (Winston 1982b).

Repeated visits to this beach over the next few years showed that stranded plastic trash could be encountered year round and that several calcified taxa besides bryozoans were consistently found attached to plastic items. Examination of freshly beached material also showed that noncalcified organisms like algae and hydroids were a part of this encrusting biota. It also seemed, at least on casual observation, that pieces beaching in summer were greener than those arriving in winter. Thus, when opportunities arose, two additional collections were made to address the following questions: (1) What were the dominant organisms on these plastic islands? (2) Were there consistent patterns of encrustation? (3) Were noncalcified organisms a

FIGURE 7.2. Gallon plastic container with large colonies of *Electra tenella*, foraminiferans, and crustose algae. North Beach, Fort Pierce, FL, study 1. *Scale bar* = 5 cm.

significant component of the community? (4) Were there any seasonal differences in the biota found on the trash? and (5) Could the flora and fauna reveal anything about the origin of the trash itself?

Florida Studies Two and Three

A summer sample was collected in July 1988, when several stormy days (E and E-NE winds up to 20 knots and 5–8 ft seas) prevented work on another project offshore. The collection was made along a 0.4-km stretch of the beach, following the high-ride drift line between the seaward ends of two public access paths. To document the occurrence of algae and other noncalcified encrusters, the collection was made during a receding tide while the freshly washed-up trash and associated flotsam was still wet from the waves. Natural flotsam cast up with the trash included *Sargassum* bunches and *Physalia* jellyfish, indicating an offshore Gulf Stream source.

The aim was to collect all fresh material brought in by the storm. Probably most of the sample was cast up by the high tide, but the transect might have also included some refloated material from previous tides. We collected 335 pieces (all those more than 2 cm in size) in plastic garbage bags to preserve moisture. On return to the laboratory, 250 pieces were measured, noted as to type and origin (if ascertainable), and examined under a dissecting microscope for attached organisms. Specimens were preserved dry, or, when necessary for later identification, saved in the appropriate preservative (formalin or alcohol). Sampling was repeated in February 1994, after 3 days of strong east winds. In this third study 126 items were collected and processed as were the summer samples.

The Western Atlantic Drift Biota

The groups of organisms found in the second and third Florida studies as well as their frequency of occurrence are summarized in Table 7.1 At least 64 taxa, representing 9 phyla, were found on the 376 items sampled. Many of these taxa were also present on collections made on Bermudian shores. Five

TABLE 7.1. Organisms encrusting Florida drift plastic (two studies).

Major group	*Estimated number of taxa*	*Rank (summer)*	*Rank (winter)*
Foraminiferans	4+	1	1
Coelenterates			
Hydroids	2+	4	2
Colonial Scyphozoa	1		
Millepora	1		
Cup corals	1		
Bryozoans	26+	2	3
Algae			
Soft (red, brown, green)	8+	3	4
Calcareous	2+	–	–
Polychaetes			
Serpulids	2+	5	5
Spirorbids	1	–	–
Other tubes	3	–	–
Sponges	2+	–	–
Colonial ascidians	1	–	–
Mollusks	6+	–	–
Crustaceans			
Acorn barnacles	2+	7	7
Gooseneck barnacles	2+	6	6
Total	64+		

groups of encrusting organisms dominated in both localities.

Foraminiferans

The most abundant encrusters on North Beach plastics were benthic foraminiferans, amoeboid protists, whose delicate protoplasm is protected by a calcareous shell or one constructed of cemented sediment. On North Beach plastics at least four taxa occurred, but most individuals belonged to one species of the genus *Acervulina* (Fig. 7.3). They may well have been the first organisms to recruit onto the plastic, as they were frequently the only organisms present on an item. Their brown-and-white or bleached white specks (about 0.5–1 mm in diameter) were numerous, occurring on 59% of encrusted items in summer and 89% in winter. They were not so conspicuous on Bermuda plastics, where occasional *Rosalina* and a *Cibicides* together with rare miliolids were identified. The presence of planktonic foraminiferans on several plastic items from Bermuda was surprising. Little is known about the ecology of encrusting foraminiferans, even though they may be important framebinders and sediment producers in reef settings. Foraminiferans have been reported from fouling studies (Woods Hole Oceanographic Institution 1952), but as microfauna, they have seldom been considered in ecological or distributional studies of marine macrofauna from either fouling or benthic habitats.

Bryozoans

Bryozoans are suspension-feeding marine invertebrates (about 5000 species worldwide) whose calcified or soft-bodied colonies can be found in almost all marine habitats, although they most commonly encrust hard substrates in shallow to shelf depths. In terms of number of items encrusted, bryozoans were the second most abundant group on North Beach plastics in summer and the third most abundant group in winter. Bryozoans were also the most diverse group in terms of numbers of species represented (28). In all three Florida studies, *Electra tenella* (see Fig. 7.2) was the most abundant bryozoan on plastic trash. The development of *E. tenella* has never been described; however, like other membraniporines, the species is presumed to be nonbrooding, with eggs spawned into seawater and developing into a triangular-shelled feeding larva (cyphonautes) that can remain in the plankton for as long as 2 months (Hyman 1959). Next in abundance on plastic trash were colonies of *Membranipora tuberculata. Membranipora tuberculata* has been reported from warm-water habitats around the world and is a dominant organism in the pelagic *Sargassum* community (Hentschel 1922; Friedrich 1969; Pestana 1985). It also occurs on other species of brown algae and occasionally on other substrates (Winston 1982a).

Three other membraniporine species, *Membranipora savartii, Membranipora arborescens,* and *Membranipora* sp., were also common (Winston 1982a), which was not surprising as their cyphonautes larvae could be expected to be carried long distances by ocean currents. It was more surprising that 23 species of bryozoans with nonfeeding or brooded larvae or both were also found on plastic, some of them more than once (Figs. 7.3 and 7.4). Larvae of these species, at least in laboratory studies, settle within a few days.

Bryozoans were similarly common in collections made from around Bermuda. *Electra tenella* and *M. tuberculata* were also frequent epibionts on pelagic plastics from Bermuda (Gregory 1983) together with at least another dozen unidentified species.

Hydroids

Hydroids, sessile colonial coelenterates (about 2000 species worldwide) whose colonies are also commonly found in fouling and hard substratum communities and whose feeding polyps are carnivorous upon zooplankton, were the second most abundant group on North Beach plastics in winter and the fourth most abundant group in summer. Hydroids were one of the first groups of organism ever reported from floating plastic

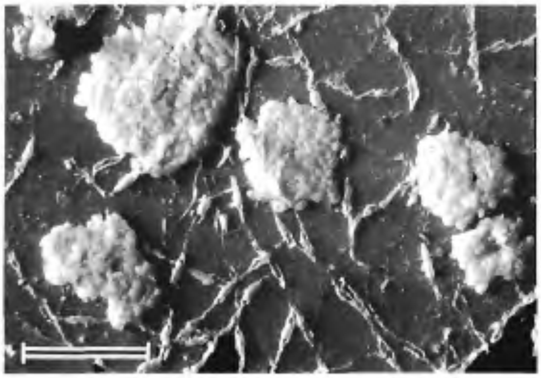

FIGURE 7.3. *Acervulina* sp. (foraminiferan) and bases of *Aetea* (bryozoan) colonies. North Beach, Fort Pierce, FL, study 2, item No. 184. *Scale bar* = 1 mm.

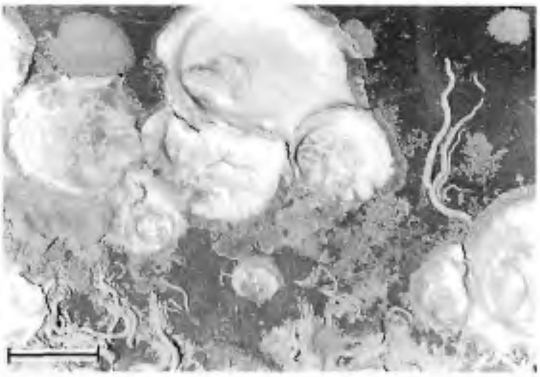

FIGURE 7.4. Portion of plastic container encrusted by mollusks, serpulids, bryozoans, and crustose algae. North Beach, Fort Pierce, FL, study 1. *Scale bar* = 1 mm.

debris (Carpenter and Smith 1972). However, because hydranths and hydroid colonies themselves are short lived and noncalcified, only the more heavily chitinized stolon regions usually remain to be found on beached debris. On dry or wet plastic their delicate traceries were barely discernible, but examination under the microscope showed that there were few pieces of plastic debris without them. It was clear that the stolons found represented more than one species; however, because hydranths and gonophores (reproductive chambers) are necessary to identify hydroids, no species identifications were possible. The few intact colonies seemed to belong to *Clytia* or *Halecium* species known as minor members of the *Sargassum* community. Larvae of these species are nonfeeding ciliated planulae that would normally attach in a few hours or days (Calder 1986).

Hydroid colonies, including species of *Clytia, Halecium,* and probably *Obelia* and *Sertularia,* were also commonly encountered on Bermuda plastics but few specimens were intact, and complete colonies were generally restricted to freshly beached material.

Algae

Algae, plants from a number of different major groups lacking certain structures (true roots, stems, leaves, and flowers) found in other plants, were the next most common encrusters on Florida plastics (Figs. 7.2 and 7.4). At least two crustose (calcareous) species occurred. Noncalcareous forms displayed morphology ranging from films to filaments and even included a young *Sargassum* recruit. Algae are common fouling organisms (Woods Hole Oceanographic Institute 1952), and are found in the *Sargassum* community. For example, calcerous *Fosliella* algae covered 1%–2% of the surface of *Sargassum* washed up on a Bermuda beach (Pestana 1985). They are also important in shallow benthic habitats and as framework builders and binders on reefs.

Algae were similarly common on the pelagic plastic stranding on Bermuda beaches. Of coralline taxa, *Fosliella* was most frequent (Gregory 1983), although *Jania, Mesophyllum, Lithophyllum,* and *Amphiroa* were tentatively identified also.

Tube-Building Polychaetes

Serpulids and spirorbids were also common encrusters of North Beach (Fig. 7.4) and Bermuda drift plastics. Sessile calcareous tube-building, filter-feeding polychaetes of the families Serpulidae and Spirorbidae are common and widely distributed in fouling and shallow water communities. Most ser-

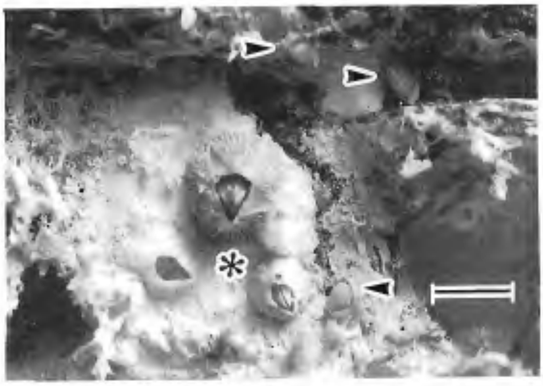

FIGURE 7.5. Plastic debris encrusted by acorn (*asterisk*) and goose (*arrows*) barnacles. North Beach, Fort Pierce, FL, study 3, item no. 61. *Scale bar* = 1 cm.

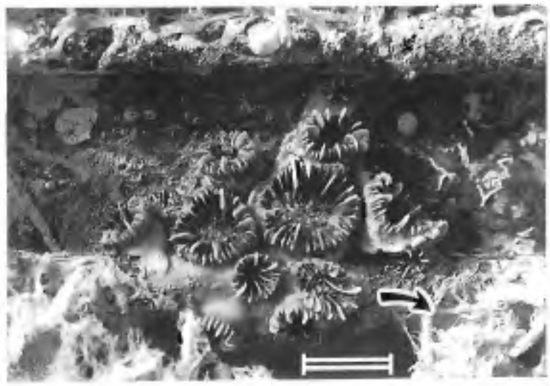

FIGURE 7.6. Plastic debris encrusted by hidden-cup corals (*Phyllangia americana*) and sponge (*arrow*; only dried fibrous skeleton remaining). North Beach, Fort Pierce, FL, study 3, item no. 61. *Scale bar* = 1 cm.

pulid tubes from the North Beach locality probably belonged to a species of *Hydroides*, but species identification was not possible from tubes alone. Tube forms of Bermuda material suggested that the most common taxon there was *Spirorbis corrugatus*, with *Spirorbis spirillum*, *Spirorbis borealis*, and *Hydroides dianthus* of lesser abundance. These species are also a conspicuous, if minor, element of the *Sargassum* community (Butler et al. 1983).

Barnacles

Next most abundant were cirripede crustaceans or barnacles (Fig. 7.5). Barnacles are a diverse and varied marine group with more than 1400 species, many cosmopolitan. Adults are shelled, sessile, and attached to hard substrata or other organisms. They feed on plankton or other particles captured or filtered by cirri. Generally, egg masses are brooded to the first nauplius stage larva, then shed into seawater where later larval stages are planktonic before settling and metamorphosing into sessile adults (Southward 1986).

Stalked lepadomorph or goose barnacles were the barnacles most frequently encountered on drift plastics from both Florida and Bermuda. This is not surprising because as a group they prefer floating substrates. The most frequently identified species was *Lepas anatifera*. The taxon considered typical of drifting *Sargassum*, *Lepas pectinata*, was not identified at North Beach and was quite rare on Bermudian artifacts. Stalkless acorn barnacles attach to both fixed and floating objects. At least two species of acorn barnacle, *Balanus eburneus* and *Balanus amphitrite amphitrite*, have also been recorded.

In addition to these dominant organisms, members of other taxa more rarely encountered on North Beach and Bermuda drift plastics included sponges, corals (Fig. 7.6), fire coral (*Millepora* sp.), octocorals, gorgonians, ascidians, colonial scyphozoans, and bivalve mollusks (including *Chama*, *Pteria*, *Anomia*, *Pinctada*, *Isognomon*, and *Crassostrea*). Membranous sabellid polychaete tubes and mud tubes that could have belonged to either polychaetes or amphipods were also noted. Occasional crabs (*Planes minutus*) were associated with larger plastic artifacts (e.g., crates) in the Bermudian wrack.

Community Recruitment

The epibiota encrusting North Beach plastics is recruited from several sources. Obviously, the most significant source of recruits should be organisms from the closest natural habitat whose larvae are drifting in the same currents. The four or five dominant species, including *Electra tenella* and *Lepas* spp., are all species common to natural flotsam, a habitat which, although long known, seldom receives ecological attention (Friedrich 1969). The *Sargassum* community is probably another major source of recruits. The second most common bryozoan, *Membranipora tuberculata,* is a dominant organism in this community (Hentschel 1922; Friedrich 1969; Pestana 1985). Several organisms frequently encountered on plastic (e.g., hydroids and serpulids) may also be recruited from the *Sargassum* community. The remaining epibionts may be recruited from any and all environments that voyaging plastic "islands" pass over, including shallow coastal and fouling communities (e.g., *Crassostrea* or *Balanus amphitrite amphitrite*), and coral reefs (e.g., corals, sponges, *Millepora*). Drift substrata are most likely to be settled by species with long-lived larvae; however, the data show that species with short-lived larvae may also recruit, perhaps when their larvae are carried to the surface by storms or during periods of upwelling such as on the Florida shelf during summer (N. Smith 1981; Worth and Hollinger 1977). While most of the normally benthic species appear to have originated in Florida or the Caribbean, at least one exotic bryozoan species was found. A *Thalamoporella* species never before reported from Florida or the Caribbean was collected in studies one and three; it most closely resembles *Thalamoporella evelinae,* a species described from Brazil (Marcus 1941).

Seasonal Differences

The same five groups of organisms dominated the Florida community in summer and winter, although in a slightly different order. One seasonal difference was in the relative abundance of the two most common bryozoans. In summer, *Electra tenella* encrusted 14% of the collected items and *Membranipora tuberculata* encrusted only 4%, while in the winter sample, *M. tuberculata* was slightly more abundant (10%) than *E. tenella* (8%). It had been thought that the greener appearance of summer drift plastic might result from the presence of more locally derived trash (perhaps from outflow from the Indian River coastal lagoon). This hypothesis was not upheld; however, the samples did show clear seasonal differences both in levels of encrustation by organisms and in the amount of tar present. In the summer sample, 60% of plastic items were encrusted by at least one kind of organism, versus 37% in the winter. The pattern for tar was reversed with only 16% of plastic items having noticeable amounts of tar on them in July versus 52% in February.

Reproduction

It is clear that at least some of the encrusting organisms found were able to reproduce on their plastic islands. Although reproduction of the membraniporine bryozoans, most common on the trash, was not demonstrable because they spawn directly into the sea, the large colony sizes found indicated that they had attained sexual maturity. Ovicelled colonies of two brooding bryozoans were found in the Florida samples; one was the previously unrecorded *Thalamoporella evelinae* and the other was *Bugula minima,* a Florida–Caribbean species (Winston 1982a). Crustose algae with reproductive structures (conceptacles) were observed on both Florida and Bermuda material, and a large serpulid tube, with several similar small tubes aggregated around it, was noted in one instance. Gastropod egg cases were also found on some plastic items, although adult gastropods were never present.

Biotic Interactions

Presumably, motile fauna (other than rare crabs) abandon their host item before or when it reaches the surf zone. However, there was ample evidence of grazing in the form of numerous teeth marks, scrapes, and gouges left on the plastic. The teeth of sharks make distinctive serrated impressions (Fig. 7.7). Older pieces, with crazed or partially degraded surfaces or both, often had large numbers of tooth marks. Whether fish were attracted to the plastic because of its encrusting biota is not known, but barnacles, one of the abundant groups, are certainly eaten by many groups of fish, including wrasses, parrotfish, and wreckfish (Southward 1986). The predation intensity suggested by tooth marks is supported by the numerous observations of increased fish numbers associated with floating objects of all kinds (Hunter and Mitchell 1966; Hunter 1968; Fedoryako 1988).

The smooth hard surfaces of the plastic may make it less hospitable to smaller invertebrate grazers and predators than a layered multibranched clump of *Sargassum* or a spongy, easily penetrated piece of drifting wood, but there is some indirect evidence that invertebrate predators may occasionally be present. Membraniporine bryozoans produce spined zooids in response to nudibranch predation (Harvell 1984). In one instance, three large circular *Electra tenella* colonies were found with an inner (older) zone of unspined zooids and an outer (younger) zone of spined zooids. This change suggests the arrival of a predator to their habitat island. However, it must be acknowledged that a sudden change to production of spined zooids has also been linked with a sharp increase in salinity (Hutchins 1941), possibly occurring when plastics passed from a river delta to the sea.

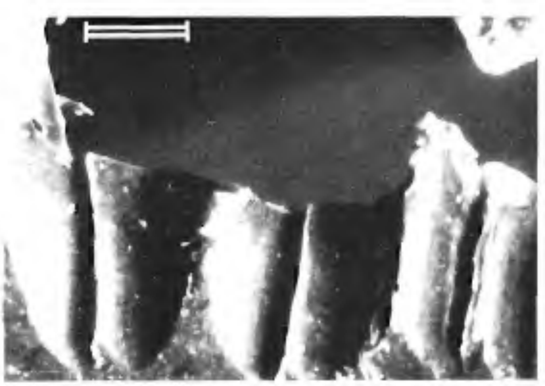

FIGURE 7.7. Shark bite in drift plastic container. North Beach, Fort Pierce, FL, study 2, item no. 132. *Scale bar* = 1 mm.

There was no indication of any biological succession on the plastic, nor was there any evidence of increased species richness with increased size of the host artifact. It has been shown for *Sargassum* clumps that age is as important as size (Fine 1970). This may also have been true for plastic islands; unfortunately, there is no good way to age [time in water] plastic. Based on observations such as brittleness and surface crazing, it appeared that large to medium-sized, middle-aged (somewhat faded, scraped, and bitten versus extremely cracked or brittle) pieces had the richest assemblages.

Biogeography and Oceanography

Plastic artifacts from up on the North Beach site have three potential sources: (1) local Florida debris (including merchant shipping and recreational cruises, commercial and recreational fishing, and inappropriate or illegal household trash disposal), in which case objects may have been in the water a few days to a few weeks; (2) sources from other countries (or states), associated with medium-distance transport (Caribbean, Brazil, or the Gulf of Mexico), in which case objects traveled several weeks or months in ocean currents; and (3) sources from other countries, associated with transoceanic movement, in which case items must have survived months or years at sea in the North Atlantic. Analysis and reflotation of encrusted plastic items showed that many (e.g., bottles, containers, washtubs, plates, cups, bowls, sandals) could be categorized as consumer or household trash from coastal or inland domestic sources and that most had floated at the surface.

Many items probably had a local source; that is, they were discarded within 500 miles of where they washed ashore. A few items seemed to have a cruise- or fishing vessel origin—Japanese containers of various types, a cruise line bag, etc. The country of manufacture of 339 of the 452 items examined in the three studies however was not identifiable because items were fragmentary or lacked labeling or imprints. Of the remaining 113 items examined, 75% had a U.S. or probable U.S. origin, and an additional 7% had labeling in English, but no further identification.

The second most important source appeared to be the Caribbean, especially the Eastern Caribbean–Lesser Antillean region, as 8% of the examined items were manufactured in Venezuela. Another 5% had labeling in Spanish; however, the exact country of origin could not be established. Items manufactured in Columbia, Mexico, Honduras, Puerto Rico, and Brazil were also represented in the three collections. Other collections made at various times along the same stretch of North Beach yielded items manufactured in Barbados and Jamaica, confirming earlier impressions (Winston 1982b) that a substantial amount of the plastic flotsam reaching this beach originated in the eastern Caribbean. Regional trading is extensive, however, and the country of manufacture was not necessarily the country of origin.

The occurrence of material from eastern Caribbean sources agrees with what is known about prevailing current patterns. Old drift studies made by the U.S. Coast and Geodetic Survey, cited in Armstrong (1994), showed that a bottle put in the sea near Caracas could reach the Florida Keys in 4 months. More recent estimates indicate a minimum time for travel from the eastern Caribbean to the North Beach latitude of the Florida coast to be about 2 months (Winston 1982b). The three largest rivers affecting the Caribbean Sea are the Orinoco, the Magdalena, and the Amazon; together they supply about 20% of the total freshwater discharge into the world's oceans. Discharge from these rivers is greatest during the rainy season (from August to October), and work by biological oceanographers using remote sensing techniques has shown that the plume of nutrients produced by their maximum outflow reaches Puerto Rico by September or October (Müller-Karger et al. 1989). It is likely that such discharge pulses add large new cohorts of plastic islands to the population already afloat, as well as affecting the amounts, types and distribution of other marine debris in the Caribbean region (Coe et al.; see Chapter 3, this volume).

Although not impossible, sources associated with transoceanic movement are least likely in the North Beach area. Two items from Portugal were collected in North Beach studies (although they could, of course, have been discarded in Brazil and reached Florida via the Guyana Current), as well as a number of items from Greece and Scandinavia. As *Sargassum* drifts into cool water, it dies and sinks to the bottom (Schoener and Rowe 1970); plastic trash does not. Sea beans, the drift seeds of tropical plants, as well as other members of the Gulf Stream community (e.g., *Velella* jellyfish and *Janthina* snails), are occasionally cast up on western Atlantic beaches; sea beans also voyage from West Africa to the Caribbean via the Equatorial Current (Turk 1982; Armstrong 1994). Given a potential life span of at least several years, there is no reason why plastic items could not make similar voyages.

As in Florida, some of the plastic debris on Bermuda's shores has a local and often recreational origin. However, it is evident that many of the larger items come from offshore if not distant sources. These sources could lie in both the heavy trans-Atlantic shipping traffic and regional cruise vessel activities. Gregory (1983) has previously emphasized the importance of the gyral circulation of the Sargasso Sea in trapping man-made litter, some of which ultimately strands on Bermuda. The Gulf Stream is also an important factor, delivering plastics from Brazil, Venezuela, and several islands of the Caribbean (e.g., Trinidad, Jamaica, Puerto Rico) to Bermudian shores.

Pacific Drift Studies: Islands Near and Far

During the same time period that North Beach trash was being surveyed, studies of drift plastic and its biota were also being carried out in the Southern Ocean and the Pacific. The first of these (Gregory et al. 1984; Gregory 1987) showed that plastic debris could be found on even remote subantarctic islands, and beyond the Polar Front into the Southern Ocean itself. Although Southern Hemisphere debris inputs are minor compared to those of the much more heavily populated Northern Hemisphere, they are still significant (Gregory and Ryan, Chapter 5, this volume). Debris adrift in these waters can be transported around the globe in as little as 3–4 years via the West Wind Drift and Circum-Antarctic Current.

Further work by Gregory (1990a, 1990b) at numerous mainland and island sites ranging from tropical to subantarctic latitudes related patterns of debris abundance and distribution to surface currents and prevailing wind regimes. Surveys carried out on isolated and unpopulated islands of the southwest Pacific showed that much of the identifiable marine debris came from oceanic sources, often distant-water fishing or shipping activities. On populated remote islands, local sources were always important, but there was also an oceanic source consisting of objects that, by their brittle character and level of encrustation, were considered to have been adrift for some time. In contrast, on urban New Zealand shorelines and closely adjacent islands much of the debris came from local sources.

Pacific Encrusting Biota

There were striking similarities between the community found encrusting drift plastic in warm waters of the Western Atlantic (Carpenter and Smith 1972; Winston 1982b; Gregory 1983) and that in the Pacific. In warm and temperate water areas of the Pacific, plastic debris is also encrusted by Bryozoans, especially *Membranipora tuberculata* (which has been found on beached debris at sites from Northern New Zealand, Australia, Norfolk Island, Raoul Island, Fiji, Rarotonga, and Tongatapu), crustose algae, serpulids, and acorn and goose barnacles (Fig. 7.8). A lone hermatypic coral of the kind often found attached to floating wood has been recorded from a plastic debris item on Raoul Island (29° S). The common reddish-pink encrusting reef-dwelling formaminiferan, *Homotrema rubra,* has also been noted on drift plastics from Raoul Island and Tuvalu (Gregory 1990b, Fig. 12). The extent of encrustation was less on subantarctic items, with only lepadomorph barnacles and spirorbid polychaetes recorded (Gregory 1990a). Fresh specimens of the well-known tropical Indo-Pacific oyster *Lopha cristagalli,* which had a solitary previous record from the northernmost New Zealand (Parengarenga, 34° 30′ S) is a recent exotic discovery from a remote southern South Island beach (Fig. 7.9); in both instances it was attached to a tangled rope mass.

In a detailed study Stevens (1992) examined more than 3000 items from 37 km of coastline in northern New Zealand. On the 228 items of drift plastic that were encrusted by one or more organisms, a biota dominated by sessile calcified organisms was found which included bryozoans, barnacles, tubeworms, calcareous algae, foraminiferans, and hydroids. The community was similar to, but richer in species, than its Western Atlantic counterpart. The species richness, frequency of occurrence, and diversity of epibionts on these 228 items is summarized in Tables 7.2 and 7.3 and further illustrated in Fig. 7.8 (for New Zealand in general). As in the Western Atlantic, bryozoans dominated in terms of number of species (58). However, *Membranipora tuberculata* was the most abundant and *Electra angulata* (the Pacific counterpart of *Electra tenella*) was much less common. There were 26 bryozoan species new to the region, including 3 undescribed species, 2 of them only known from drift plastic. Many colonies were sexually mature.

Numerous epibionts overgrew others. In general, bryozoans were able to cover most other taxa, including other bryozoans. The most successful overgrowth was by *Celleporina hemiperistomata,* with *Watersipora subtorquata, Electra angulata,* coralline al-

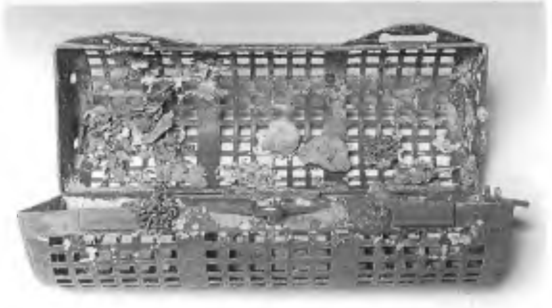

FIGURE 7.8. Heavily encrusted bait box (length, 33 cm) with bryozoans, mollusks, worm tubes, foraminiferans, and crustose algae. North Beach, Chatham Island, New Zealand.

FIGURE 7.9. *Lopha cristagalli*, a common tropical Indo-Pacific mollusk species; one of many attached to a tangled mass of plastic rope. Coal Island, Preservation Inlet, New Zealand. (Collected by J. Lindquist.)

gae, and the tubeworm *Hydroides elegans* of progressively decreasing significance. Two species, the barnacle *Lepas anatifera* and the bryozoan *Cryptosula pallasiana,* were present exclusively on plastic items with positive buoyancy, while four bryozoans (*Eurystomella forminigera, Foveolaria cyclops, Galeopsis porcellanicus,* and *Smittoidea maunganuiensis*) were restricted to negatively buoyant material. More than 40 species from all taxonomic groups were present on both buoyant and nonbuoyant debris.

Community Development and Biotic Interactions

Beach-cast material preserves only sessile organisms with hard skeletons (with perhaps a few desiccated remnants of soft-bodied forms). It gives little indication whether soft-bodied or motile animals were originally present in the community. To address that problem, Stevens (1992) moored 87 plastic bottles—polyethylene terephthalate (PET) and high density polyethylene (HDPE)—in seawater at depths of 0 and 10 m near the Leigh Marine Laboratory, on the east coast of New Zealand's North Island, 50 km north of Auckland. The development of communities fouling the plastic was followed over a period of 10 months. Sixty-seven sessile taxa were found on moored plastic items. Substrata were dominated by algae and hydroids, with algae cover increasing and hydroid cover decreasing during the 10-month experiment. Serpulid tubeworms and barnacles were also common. In addition, 32 motile taxa, mostly

TABLE 7.2. Species richness and frequency of occurrence of epibiontic taxa recognized on drift plastic items along northern New Zealand coastline (Stevens 1992).

Type of organism	*Number of species (+ unidentified)*	*Single occurance of species*	*Rare (<5)*	*Few (5–10)*	*Common (11–30)*	*Abundant (31–50)*
Bryozoans	58 (4)	23	20	10	4	–
Mollusks	8 (1)	6	2	–	–	–
Tubeworms	5 (3)	3	–	–	2	1
Barnacles	5 (0)	1	–	2	1	1
Foraminiferans	4 (0)	3	–	–	1	–
Ascidians	1 (0)	1	–	–	–	–
Hydroids	0 (1)	–	–	–	1	–
Algae	1 (1)	–	–	–	–	1
Total	82 (10)	37	22	12	9	3

TABLE 7.3. Frequency of species (bryozoans and total encrusting epibionts) found on drift plastic items along the northern New Zealand coastline (Stevens 1992).

Number of species per plastic item	*Number of occurrences (bryozoans only)*	*Number of occurrences (all species)*
1	74	121
2	1	39
3	2	25
4	1	10
5	1	8
6	0	4
7	0	6
8	0	4
9	0	3
10	0	3
>10	0	5
Total	79	228

crustaceans (crabs and amphipods) and polychaetes, were recorded. No bryozoans occurred on surface-moored bottles, and ***Membranipora tuberculata*** was not among those bryozoans occurring on the bottles at the 10-m depth.

This study of moored items demonstrated that the presence of larvae in the water column was the most influential factor controlling community development. Successional stages (which have sometimes been described from fouling communities) did not occur on the moored plastic and hence could not be used to age an item. However, growth rates were determined for organisms common on moored plastic over several months, and it was clear that similar studies could serve to establish a minimum time in the sea for a drift item. Stevens suggested that barnacles and bryozoans might be best for this purpose.

Stevens observed juvenile fish living inside some of the bottles and other fish grazing on bottle surfaces. Invertebrate grazers (amphipods, gastropods, chitons) were also common. During the 10-month experimental period the organisms encrusting the plastic actually changed the level at which bottles floated. Algae-covered bottles floated higher in the water than clean bottles, and encrustations of barnacles, mollusks, ascidians, and sponges forced bottles down.

Oceanography

In Pacific beach-cast plastic items, the portion of material with calcified and other epibionts varied geographically (locally it may exceed 20%; see Table 7.4), and perhaps seasonally, although this latter claim needs elaboration. Frequency of encrustation, in general, was highest at rarely visited remote localities and was least on popular recreational shores near urban centers and other upland sources.

Discussion

Encrusting Epibiota

In tropical, subtropical, and warm-temperate waters a distinct community of organisms encrusts drift plastic. The same groups of organisms, and apparently even some of the same species, have been found in widely scattered sites in the Caribbean, the Western

TABLE 7.4. Percent frequency of occurrence of encrusted, beach-cast plastic items found in selected North Atlantic and southwest Pacific Ocean localities.

Locality	*Proportion of encrusted items (%)*
Bermuda	
Grenadier Bay	5
Nonsuch Island	16
West Whale Bay	15
United States	
Fort Pierce (Florida)	37-60
Raoul Island	
North Coast	7-30
Denham Bay	13
Boat Cove	10
New Zealand (+, remote localities-*, recreational and urban localities)	
Northeast (North Island)	7*-14+
West Coast (North Island)	5-10
Southland (South Island)	<1-5
Subantarctic Islands	0-<1
Australia	
Queensland (north of Townsville)	<5->10
Tasmania	<3

Atlantic, and the Pacific. The community is dominated by sessile animals and plants known to occur on natural floating substrata such as tropical seeds, logs, and pumice, which are also known to drift many thousands of miles (Bryan 1971; Jokiel 1989; JMB Smith 1990, 1992), as well as on pelagic sea turtles and sea snakes. The epibionts of plastic also include species known from the pelagic *Sargassum* community. Probably next in importance on drift plastic are cosmopolitan warm-water fouling species, normally found in harbor and coastal environments, whose larvae tend to settle at or near the water surface and that have already been spread around the world by shipping vessels. Limited information on the fouling of pelagic plastic litter and trash in colder waters indicates fewer taxa may be involved.

Potential for Dispersonal of Marine Organisms

Individual items also have the potential to pick up segments of whatever benthic community they pass over on their voyages. In this way, drift plastics increase the potential for dispersal for a number of groups of marine organisms including those with short-lived larvae, as is illustrated by the finding that species of several groups in which brooding takes place reach reproductive condition on floating plastic (e.g., bryozoans, gastropods, and crustose algae). As a transoceanic dispersal mechanism, plastic substrata are more likely significant for colonial groups (in which one colony can become a founder population) than they are for solitary organisms. In bryozoans, cross-fertilization between colonies is normal in sexual reproduction, but when grown in isolation, a high proportion of species have the ability to self-fertilize and produce daughter colonies (Maturo 1991).

Drift plastic substrata can and do serve to bring in new species. This is shown by two examples from the limited work done so far with *Lopha cristagalli* in the Pacific (see Fig. 7.9) and *Thalamoporella evelinae* in the Atlantic. Compared to the numbers of larvae dumped into a harbor by discharge of ballast water (Carlton 1987; Carlton and Geller 1993), the contribution of floating plastic to environmental problems associated with the introduction of aggressive alien taxa is probably low. However, the following points should be kept in mind.

Dispersal by plastic debris is most likely to affect closely adjacent coastal regions (e.g., spread of an exotic species from a site of introduction like a populated harbor to nearby islands). Trash can be rapidly dispersed along a shoreline by currents. For example, a mooring lost at one New Zealand locality was beached 3 weeks later 30 km away (Stevens 1992).

The total habitat is still increasing and is semipermanent. Individual items appear to have the potential to make one or more circuits of the world oceans (e.g., the Gulf Stream or the Southern Ocean) before fragmenting, sinking, or being driven ashore.

Even when the number of larvae of a particular species colonizing plastic was low, a favorable set of circumstances could change that picture. For example, in regions like the Caribbean where seasonal outflow from rivers has a strong influence on hydrography, a chance combination of the appearance of a large cohort of plastic islands (carried from coastal and upland sources by the rivers) with an especially large cohort of larvae in any of the coastal benthic habitats (e.g., reefs and shelfs) that plastics pass over could result in a transport event large enough to affect the biota of distant shores.

More than 200 plants and animals are known from fouling communities (Woods Hole Oceanographic Institution 1952), and many of them have already effected a cosmopolitan distribution by traveling on ships. Travel by vessel fouling moves organisms rapidly through environments that are novel and often hostile in terms of temperature and salinity, yet some may survive. For example, a collection made of the fauna from the sides of an old ship that had come from Bermuda and was being broken up in Copenhagen harbor (where the water was colder and much less saline) yielded gravid jewel box clams (*Chama* sp.) as well as live crabs and blennoid fish (Bertelsen and Ussing 1936). A slow voyage on plastic (especially when conditions are favorable) would give encrusting biota much better chance of survival.

Potential for Dispersal: Terrestrial Organisms

As unlikely as it may seem, transport of terrestrial organisms (plants, invertebrates, and vertebrates) possibly has a greater probability of significant biological impact (Fig. 7.10). A number of studies have shown that insects, snails, isopods, millipedes, and plants can survive transport, for example, on rafts of vegetation or logs or both (Wheeler 1916; Heatwole and Levins 1972). Because of its smooth, nonporous surface, plastic is not as well suited to their survival as natural vegetation, but the report of viable seeds being transported in a plastic toy boat (West 1981) strongly suggests the possibility that insects or other hard-shelled invertebrates could be passively carried in the same manner.

Rafting long distances may be extremely unlikely for vertebrates (e.g., lizards, rats) because the very large masses of trash noted in some urban harbors are unlikely to stay together in stormy seas. The greatest potential for impact is local, i.e., the introduction of pests like rats from populated coasts to nearby islands where attempts are being made to preserve an endangered native biota. For example, beach cleanups around New Zealand show plastic regularly constitutes 70% or more of beach litter (Smith and Tooker 1990), and this suggested to Gregory (1991) that metropolitan and land-source aggregations of marine debris could end up on nearby islands. It is conceivable that islands of high conservation value and meriting heritage or scientific reserve status, with biotas supposedly protected from disturbance, could unknowingly be placed at risk. Events of this kind could lead to the introduction of exotic and aggressive alien taxa, thus eroding

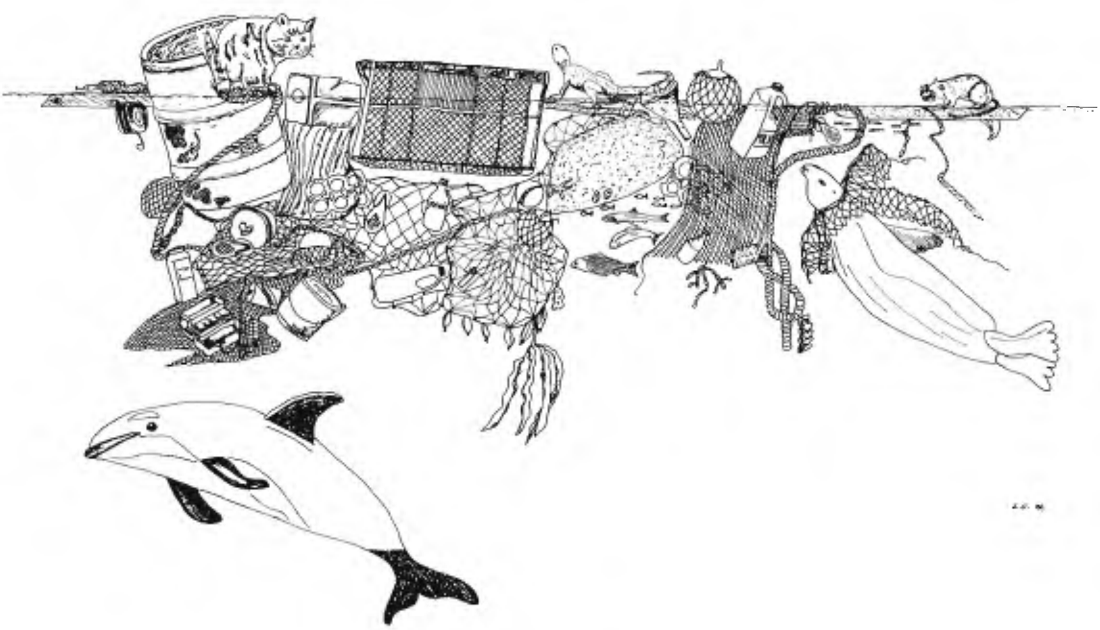

Figure 7.10. Artist's conception of rafts of plastic debris as a dispersal agent for marine and terrestrial organisms.

or rapidly destroying years of environmental effort and progress. It is a danger of which those who manage or have stewardship over protected coastal commons should remain cognizant (Gregory 1991).

Oceanography

There is demonstrable need for collaborative research efforts among marine biologists, geologists, physical oceanographers, and students of man-made persistent pelagic debris (including plastic). The interactions could be scientifically rewarding and also have practical relevance to marine environmental management.

Lack of biological succession on plastic islands shows that their time afloat cannot be determined by community structure as Gregory once envisaged (1990b). However, colony size and growth rates of key taxa may permit minimum age estimates. Through timing of stranding events, marine debris research may assist oceanographers in relating peak river outflow in source regions to pollution or contamination events (or both) some distance away. A comparable example is the study of commercial fishery point sources and litter reaching the Texas coast (Miller et al. 1995). On the other hand, studies of epibionts may identify discrete and different water masses through which plastic debris has passed and hence assist in hindcasting currents and circulation patterns. An example is the forensic study of *Lepas* on an overturned yacht hull found to the east of New Zealand in 1989, which confirmed drift from north to south—a direction contrary to accepted ideas of the prevailing current sets (Foster, n.d.).

Final Fate

The community that develops on a piece of debris can make it float higher in the water or sink below the water surface, potentially affecting its trajectory with respect to ocean currents (whether primarily wind-driven or current-driven), and its total survival time, as well as whether it ends up on the bottom in shallow, continental shelf, or abyssal depths. Encrusting organisms may aid in breakdown of plastic or conversely may protect it from sun damage and desiccation effects. These aspects of the problem still need to be addressed, for very few studies have done so (Sibley and Strickland 1989). Plastic debris settling to the sea floor may also provide substrata suitable for colonization by a varied biota. Harms (1990) found 20 species inhabiting plastic debris dredged from the Elbe estuary. Rundgren (1992) studied plastic debris on the bottom at 18 sites around False Bay, near Cape Town, South Africa. Colonization of plastic shopping bags attached to the bottom at 5 m depths by benthic organisms (barnacles and mussels) took place within 2 weeks. Other observations included entanglements of sea urchins and sea fans with plastic, encrustation of plastic by an anemone and calcareous algae, and the presence of anoxic black sediment under a partly buried bag. Benthic ecologists have been putting plastic into the ocean for the last 30 years also, either as fouling substrata (Walters 1992) or as frames and supports for benthic panels, collectors, or other experiments. These submerged plastics have become experiments themselves, if unintentional ones, and input from ecologists should be sought.

In some areas plastic may be detrimental to benthic communities and demersal fisheries (Nash 1992). It was first noticed to impact fisheries almost 20 years ago (Hollström 1975), and the problem has not gone away. Nor is its effect restricted to urbanized coasts, for debris is moved and sorted by winds and currents (Bingel et al. 1987; Williams et al. 1993; Ribic et al., Chapter 4, this volume; Coe et al., Chapter 3, this volume; Matsumura and Nasu, Chapter 2, this volume; Gregory and Ryan, Chapter 5, this volume). In other areas, like the deep sea, sunken plastic might be a boon, providing food and substrate. It has been suggested that "whale falls," dead bodies of whales whose remains persist for several years, may provide a food resource and serve as a dispersal pathway for deep-sea vent organisms (CR Smith 1992; Ward 1994). We have begun to study the potential impact of benthic organisms whose larvae hitch a ride at the ocean surface, but it may be that our sunken trash is leaving a Hansel and Gretel-like trail of plastic crumbs through the ocean basins to guide benthic organisms to new settlement areas.

The epibionts of pelagic plastics may also be contributing increasingly to carbonate sediment budgets. Epibionts of sea grasses (Land 1979) and *Sargassum* (Pestana 1985) are known to be important contributors to the carbonate budget of tropical and subtropical, shallow marine sediments. Also, significant calcification rates, for bryozoans rapidly colonizing plastic substrates fixed close to the bottom in shallow temperate water near the site of Stevens' (1992) observations, have recently been recognized (Smith and Nelson 1994).

Conclusions and Recommendations

From this review a number of general conclusions and recommendations can be made. The scope of biological interactions with marine plastic debris is broad (see Fig. 7.10). The environmental problems receiving the most publicity so far are ingestion and entanglement, together with those of aesthetic values. The aggregation of fishes around floating objects, and the curiosity-driven attraction of some smaller marine mammals to flotsam are well known. However, it is only recently that the attention of the scientific community has been drawn to the significance of an encrusting (and pseudo-planktonic) biota and to the potential that pelagic plastics offer as vectors in both short- and long-distance dispersal of marine and possibly terrestrial organisms. Four primary aspects warrant further research.

1. Fully establish all facets of the biological significance of plastic both afloat and once it has settled to the sea floor. The latter is likely to be linked to fishery resources and their management.
2. Networking with beach cleanup groups to accumulate data on distributions of encrusting organisms. Study and determination of growth rates of indicator taxa may permit aging of pelagic plastic and compilation of guidebooks or brochures (or both) of common epibionts on drift plastic.
3. There is urgent need for study of biofilms on pelagic plastics and the role of microbial processes in the degradation of pelagic plastics.
4. Studies of existing pest exotics should be used to pinpoint characteristics of other species that might become problems, assess the likelihood of their doing so, and predict when and where their impact would be. For example, the zebra mussel (*Dreissena polymorpha*), a native of the Black and Caspain Seas, was accidentally introduced into the Great Lakes in 1986, probably via ballast water, and has become a major problem in North American freshwater habitats. Its damaging effects result from its life history characteristics: rapid growth, high fecundity, ability to attach securely to aquatic structures, and efficiency in filter feeding that can deplete the food resource for native organisms (Marsden 1992). An exotic serpulid introduced into New Zealand waters caused similar problems in a more limited area because of its ability to form massive growths on boats and submerged structures (Read and Gordon 1991). Such characteristics could be assessed for other potential invaders.

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