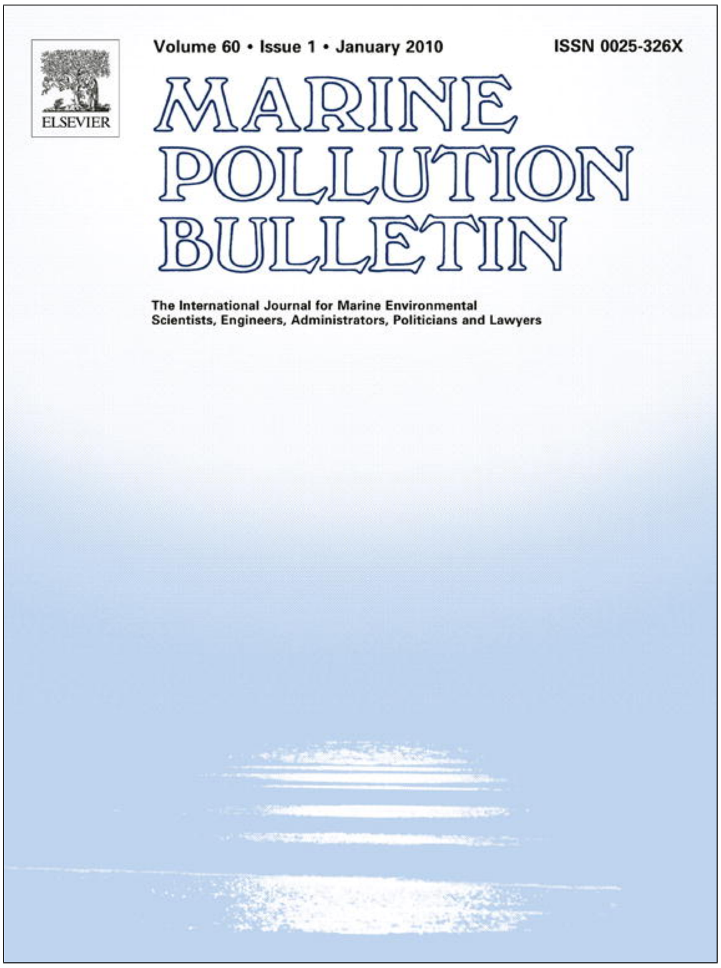
Volume 60 • Issue 1 • January 2010
ISSN 0025-326X
ELSEVIER
MARINE POLLUTION BULLETIN
The International Journal for Marine Environmental Scientists, Engineers, Administrators, Politicians and Lawyers

Marine Pollution Bulletin 60 (2010) 131–138

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Assessing marine debris in deep seafloor habitats off California

Diana L. Watters [a,*], Mary M. Yoklavich [a], Milton S. Love [b], Donna M. Schroeder [c]

[a] *Fisheries Ecology Division, Southwest Fisheries Science Center, National Marine Fisheries Service, 110 Shaffer Road, Santa Cruz, CA 95060, USA*
[b] *Marine Science Institute, University of California, Santa Barbara, CA 93160, USA*
[c] *Minerals Management Service, 770 Paseo Camarillo, Camarillo, CA 93010, USA*

ARTICLE INFO

Keywords:
Delta submersible
Submarine canyons
Continental shelf
Benthic communities
Video survey
Plastics

ABSTRACT

Marine debris is a global concern that pollutes the world's oceans, including deep benthic habitats where little is known about the extent of the problem. We provide the first quantitative assessment of debris on the seafloor (20–365 m depth) in submarine canyons and the continental shelf off California, using the *Delta* submersible. Fishing activities were the most common contributors of debris. Highest densities occurred close to ports off central California and increased significantly over the 15-year study period. Recreational monofilament fishing line dominated this debris. Debris was less dense and more diverse off southern than central California. Plastic was the most abundant material and will likely persist for centuries. Disturbance to habitat and organisms was low, and debris was used as habitat by some fishes and macroinvertebrates. Future trends in human activities on land and at sea will determine the type and magnitude of debris that accumulates in deep water.

Published by Elsevier Ltd.

1. Introduction

Marine debris has become a global concern, polluting habitats even in the most remote parts of the world's oceans (NRC, 2009). Debris is introduced into the marine environment by its improper disposal, accidental loss, and by natural disasters. It can be transported long distances by ocean currents and tides, and can sink and accumulate on the seafloor. A study by the National Research Council (NRC) conducted prior to the regulation of garbage disposal from ships (International Maritime Organization, 2008) reported that 1.4 billion pounds of trash entered the ocean annually from vessels alone (Goldberg, 1975). The negative impacts of this pollution are wide ranging and include aesthetic degradation of beaches, navigation hazards, and death of marine organisms and damage to their habitats.

Efforts to address concerns about marine debris have focused primarily on monitoring surveys and clean-up of the sea surface, shorelines, and shallow seafloor areas accessible to snorkelers and scuba divers (<30 m depth) (NRC, 2009). Little is known about the composition, extent and, most importantly, impacts of marine debris in less accessible areas of the seafloor in deep water (>30 m depth). From a review of the methods used to study marine debris on the seafloor (Spengler and Costa, 2008), deep-water debris was most often sampled incidentally with bottom trawl nets during surveys of benthic fauna (e.g., Galil et al., 1995; June, 1990; Moore and Allen, 2000). Bottom trawling is a relatively convenient method of collecting some types of debris from large areas of the seafloor, provides information on relative distribution and abundance of the items available to the gear, and allows close inspection and measurement of debris. However, trawl gear cannot be used effectively in complex rocky habitats where debris (particularly derelict fishing gear) may be concentrated. In addition, because the catch (including the debris) is integrated over the length of the tow (which can be several kilometers), the exact location of items cannot be determined. Trawls likely underestimate debris abundance, and completely miss some types (e.g., monofilament line) because of variable efficiency at collecting a wide assortment of shapes and sizes. Moreover, bottom trawling does not offer a useful means of assessing impacts of the debris to habitats and organisms, and can contribute its own impacts to the seafloor (Gage et al., 2005; Stone et al., 2005).

In addition to bottom trawling, Galgani et al. (1996, 2000) used manned submersibles to investigate the distribution and abundance of debris off the European continental shelf, slope, and canyons within the Gulf of Lions at bottom depths to 2700 m. Stevens et al. (2000) used sidescan sonar to locate possible derelict crab pots at 100–150 m near Kodiak, Alaska, an occupied submersible and remotely operated vehicle (ROV) to verify the sonar images, and grappling gear to retrieve the pots.

Since 1992, we have surveyed demersal fish assemblages and associated seafloor habitats at depths of 20–365 m off California using direct observation methods from the manned submersible *Delta* equipped with video cameras (Love et al., 2009; Yoklavich

* Corresponding author. Tel.: +1 8314203934; fax: +1 8314203980.
E-mail addresses: diana.watters@noaa.gov (D.L. Watters), mary.yoklavich@noaa.gov (M.M. Yoklavich), love@lifesci.ucsb.edu (M.S. Love), donna.schroeder@mms.gov (D.M. Schroeder).

0025-326X/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.marpolbul.2009.08.019

et al., 2000, 2002). We have conducted quantitative surveys in lightly and heavily fished areas, recording in situ information on abundance, species composition and sizes of fishes and invertebrates, and various aspects of their seafloor habitats. In addition, we have noted the presence of derelict fishing gear and other marine debris during these surveys.

We have used our survey databases and video archives to quantify the types, extent, and potential impacts of derelict fishing gear and other marine debris in a variety of seafloor habitats in deep water off central and southern California. The objectives of this study were to: (1) identify marine debris items and their sources; (2) describe the spatial distribution and abundance of debris; (3) evaluate impacts of debris to organisms and habitats; (4) compare attributes of debris between central and southern California study areas; and (5) assess change in density and attributes of debris surveyed off central California in 1993–1994, 1997–1998, and 2007.

2. Methods

Our study areas included submarine canyon and continental shelf locations in the Monterey Bay National Marine Sanctuary and several marine protected areas off central California, and offshore banks within the Cowcod Conservation Areas off southern California (Fig. 1). Surveys of marine debris were conducted at depths of 20–365 m off central California in 1993–1994 and 1997–1998 (1993–1994 and 1997–1998 hereafter referred to as 1990s) and 2007, and off southern California in 2002.

Marine debris items were noted by a scientific observer from inside the two-person *Delta* submersible while conducting quantitative transects during surveys of fishes, invertebrates, and seafloor habitats. Items occurring within a two- to five-meter-wide strip from the *Delta's* starboard side were described verbally by the observer. One to three video cameras recorded visual images and the scientist's narration. Transects typically were conducted at a constant speed of 0.5–1.0 knot for 10 or 15 min. The length of each transect was estimated by one of two methods: (1) from the videotape, counting the number of segments demarcated by two lasers that were mounted a fixed distance (20 or 39.5 cm) apart on either side of the camera (Yoklavich et al., 2000, 2002); (2) calculating distance from the *Delta's* navigation data (Yoklavich et al., 2007). A time code was stamped on the video, which linked each debris item to a geographic position (i.e., latitude and longitude) along the transect route. Details of our survey methodologies are described in Yoklavich et al. (2000) and Yoklavich and O'Connell (2008).

We used the archived video to review and further characterize each marine debris item, adding items not called out by the observer and assessing possible impacts of the debris to the benthic community. Our ability to identify and assess debris from the

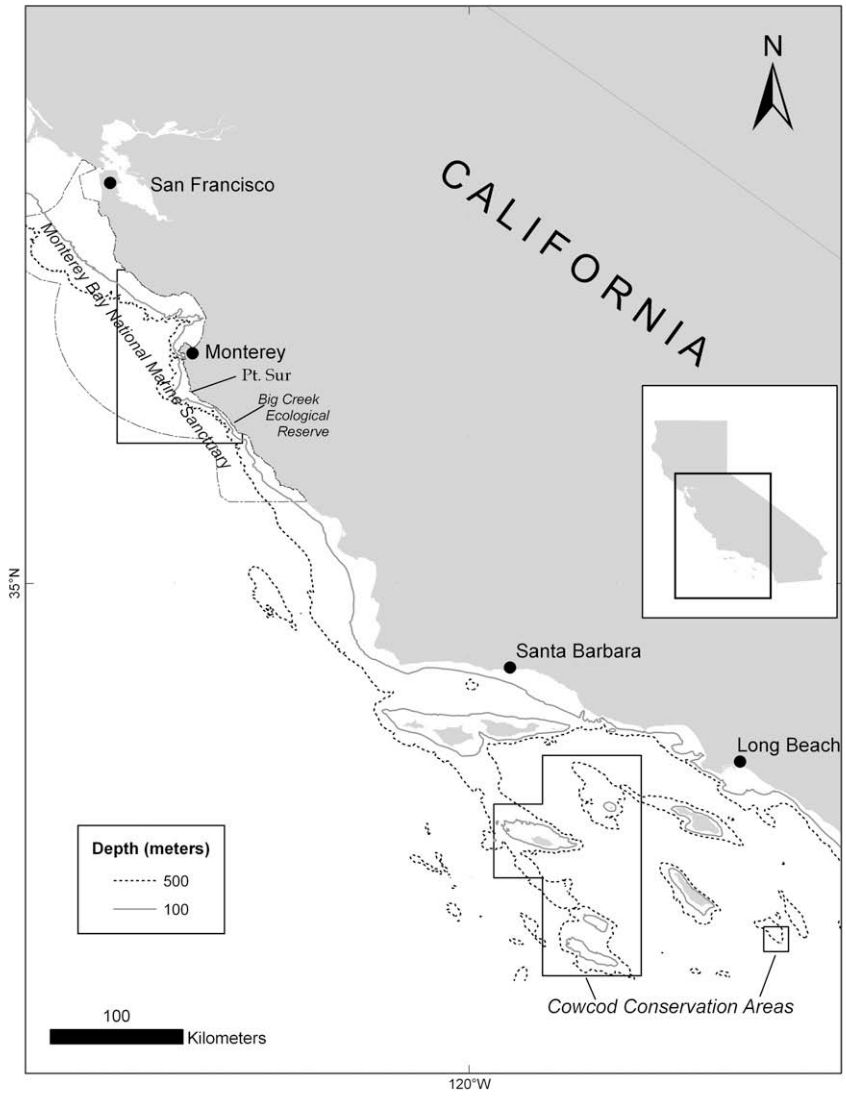

Fig. 1. Study areas (denoted by solid dark borders) off central and southern California.

videotape depended on the visibility, the degree of seafloor relief (i.e., flat or complex), and the amount of fouling of the item by invertebrates. Items that could not be seen on the video were characterized based on the observer's comments (e.g., visible to the observer but out of the video camera's view). We identified and counted types of items (e.g., monofilament line, prawn trap, beverage can), and noted their composition (e.g., plastic, wood, metal). We assessed the possible source (e.g., commercial fishing, recreational fishing, maritime or coastal) of each item. For debris that could not be linked to a specific source activity, we assigned the category "maritime or coastal". Items were assessed for degree of colonization (light, moderate, heavy) by benthic invertebrates. Debris items were evaluated as potential habitat by classifying their associations with fishes and macroinvertebrates (i.e., organisms located on, in, or nearby debris). The type of substratum (rock, cobble, soft sediment [i.e., mud, sand]) associated with debris was identified. We also noted any disturbance (e.g., scouring, breakage of invertebrates) as well as ghost fishing (i.e., capture and killing of organisms by derelict fishing gear) caused by the debris.

We calculated the density of debris (number of items/100 m) on each transect, and mapped them spatially in ArcMap 9.3. Using different distances relative to the spacing of transects (e.g., 500, 1000, 2000 m), the Global Moran's I statistic was calculated multiple times in ArcMap to determine the fixed-distance band width that maximizes spatial autocorrelation of densities. A hot spot analysis was conducted using this band width and the Getis-Ord Gi* statistic (Ord and Getis, 1995) to identify spatial clusters of transects with significantly high densities of debris. This statistic calculated a *Z* score (a measure of standard deviation) for each transect based on its density value and that of neighboring transects. Critical *Z* scores at the 95% confidence level are >1.96 for hot spots and <−1.96 for cold spots.

3. Results

3.1. Distribution and abundance of debris

Marine debris was quantified from 210 video transects conducted off central California in the 1990s (i.e., 1993–1994 and 1997–1998). Length of these transects ranged from 19 to 585 m; a total of 57,143 m was surveyed. Transects were located at Ascension, Año Nuevo, Soquel, Monterey, and Carmel submarine canyons, and continental shelf sites at Italian Ledge, Portuguese Ledge, and off Point Lobos, Point Sur, and Big Creek Ecological Reserve (BCER) (Fig. 2a). There were 803 debris items found on 75 (36%) of these transects.

The density of debris ranged from 0 to 38 items/100 m, and averaged 1.7 items/100 m (SE = 0.4). Statistically significant clusters of transects with high densities of debris (hot spots) were identified at Italian Ledge ($Z = 2.3–10.3$, $p = 0.0–0.02$), the southwestern edge of Soquel Canyon ($Z = 2.4–3.8$, $p = 0.0–0.02$), and Monterey Canyon ($Z = 2.4$, $p = 0.02$).

Marine debris was quantified from 112 transects conducted off central California in 2007. Transects ranged from 90 to 382 m in length; a total of 26,690 m were surveyed. These were located at Soquel, Monterey, and Carmel submarine canyons, Italian Ledge, Portuguese Ledge, and off Point Lobos, Point Sur, and at BCER (Fig. 2b). There were 855 debris items found on 47 (42%) of these transects.

We evaluated change in density of debris from 161 transects (40,478 m) selected from the 1990s with debris density from the 112 transects from 2007 at the same or nearby sites. There were 712 debris items found on 52 (32%) of these transects from the 1990s. Transects at Ascension and Año Nuevo submarine Canyons from the 1990s were not included in this comparison, as there were no transects conducted there in 2007. The range in density of debris in 2007 was the same as in the 1990s (0–38 items/100 m). Average density in 2007 was significantly higher than in the 1990s (2007: 3.5 items/100 m, SE = 0.7; 1990s: 2.0 items/100 m, SE = 0.5; one-tailed *t* test, $p = 0.04$). As with the earlier survey, hot spots of debris in 2007 were identified at Italian Ledge ($Z = 6.1$, $p = 0.0$), southwest Soquel Canyon ($Z = 3.1$, $p = 0.0$), and Monterey Canyon ($Z = 3.34$, $p = 0.0$).

Marine debris was quantified from 321 transects conducted in 2002 off southern California. Transect length ranged from 18 to 570 m; a total of 121,684 m of seafloor were surveyed at offshore reefs and banks within the Cowcod Conservation Areas (Fig. 2c). There were 187 debris items found on 105 (33%) of these transects. The density of debris ranged from 0 to 3 items/100 m, and averaged 0.2 items/100 m (SE = 0.02). Hot spots of debris were located at 43-Fathom Bank ($Z = 4.8–7.6$, $p = 0.0$), east of San Nicholas Island ($Z = 2.6–3.6$, $p = 0.0–0.01$), near Santa Barbara Island ($Z = 2.0–2.6$, $p = 0.01–0.04$), and Kidney Bank ($Z = 2.0$, $p = 0.04$).

The relative abundance of habitat types (i.e., types of seafloor substrata) associated with debris was compared with the total amount of habitat types surveyed (Fig. 3). Debris occurred more frequently on rock than other habitats in central California (1990s, Fig. 3a; 2007, Fig. 3b). Off southern California (Fig. 3c), debris occurred on habitats in proportion to their abundance.

3.2. Characterization of debris

Fishing activities were a dominant source of debris in both study areas (central and southern California) and time periods (Figs. 4 and 5a, b, and d). Recreational fishing was the predominant source of debris off central California in the 1990s and 2007 (92% and 93%, respectively). Commercial fishing activities (38%), maritime or coastal activity (50%), and recreational fishing (10%) contributed to the debris found off southern California.

Debris from recreational fishing off central California was composed entirely of monofilament fishing line from rod-and-reel gear (Fig. 5a), which significantly increased in density from the 1990s to 2007 (one-tailed *t* test, $p = 0.04$) (Table 1), while the density of commercial fishing debris (including longlines, nets, and traps) (see for example, Fig. 5b and d) was much lower and did not change significantly ($p > 0.05$) over time. Monofilament line from rod-and-reel gear was also the most abundant type of recreational fishing debris off southern California but was significantly less abundant than off central California (average density of 0.02 items/100 m in southern California in 2002 compared to 3.2 items/100 m in central California in 2007, one-tailed *t* test, $p = 0.0$). The density of debris from commercial fishing off southern California was similar to that off central California (Table 1).

The most abundant debris types originating from maritime or coastal activities off central California were lines, cables, beverage cans, bottles (Fig. 5c), and household items (Table 2), and the average density of items from this source increased significantly ($p < 0.05$) from the 1990s to 2007. Maritime or coastal activities were a dominant source of debris off southern California (Table 2). Although the overall average density of debris items from this source was lower in southern California in 2002 than in central California in 2007, the density of beverage cans was five times greater off southern California (0.02 items/100 m, SE = 0.005) than off central California in 2007 (0.004 cans/100 m, SE = 0.004).

Plastic was the most common debris material in both study areas (Fig. 6). Because central California was dominated by monofilament rod-and-reel line, 95% of the debris was plastic in 2007. The diverse assortment of debris off southern California most commonly was made of plastic (41%), metal (38%), and glass (9%).

The majority of debris items had colony-forming invertebrates on them. Off central California in 2007, 99% of 815 items had mod-

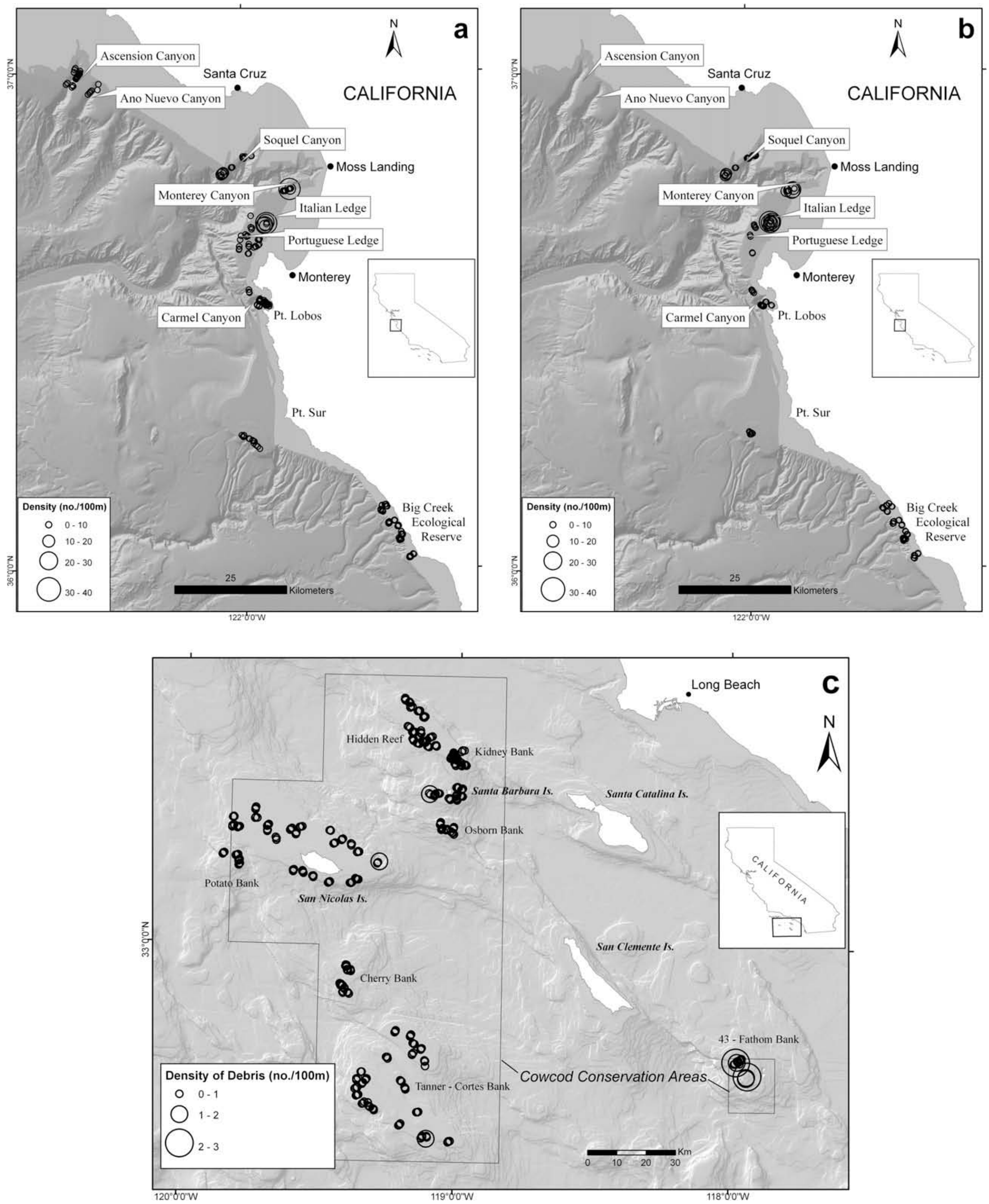

Fig. 2. Density (number of items/100 m) of debris on transects conducted from the submersible *Delta*: (a) in 1993–1994 and 1997–1998 off central California; (b) in 2007 off central California (all transects comparable with selected transects from the 1990s); and (c) in 2002 off southern California.

erate or heavy colonization, and in southern California, 88% of 162 items had moderate or heavy colonization.

3.3. Impacts of debris

Little ghost fishing was observed in either central or southern California. In both study areas and time periods, we were unable to evaluate ghost fishing for several items of fishing gear due to limited views (e.g., invertebrate colonization obstructing view, incomplete observation of item). Off central California in the 1990s, six of eight nets were not ghost fishing and two could not be evaluated; one trap was ghost fishing and another could not be evaluated. Off central California in 2007, two of four nets were not ghost fishing and two could not be evaluated; four traps could

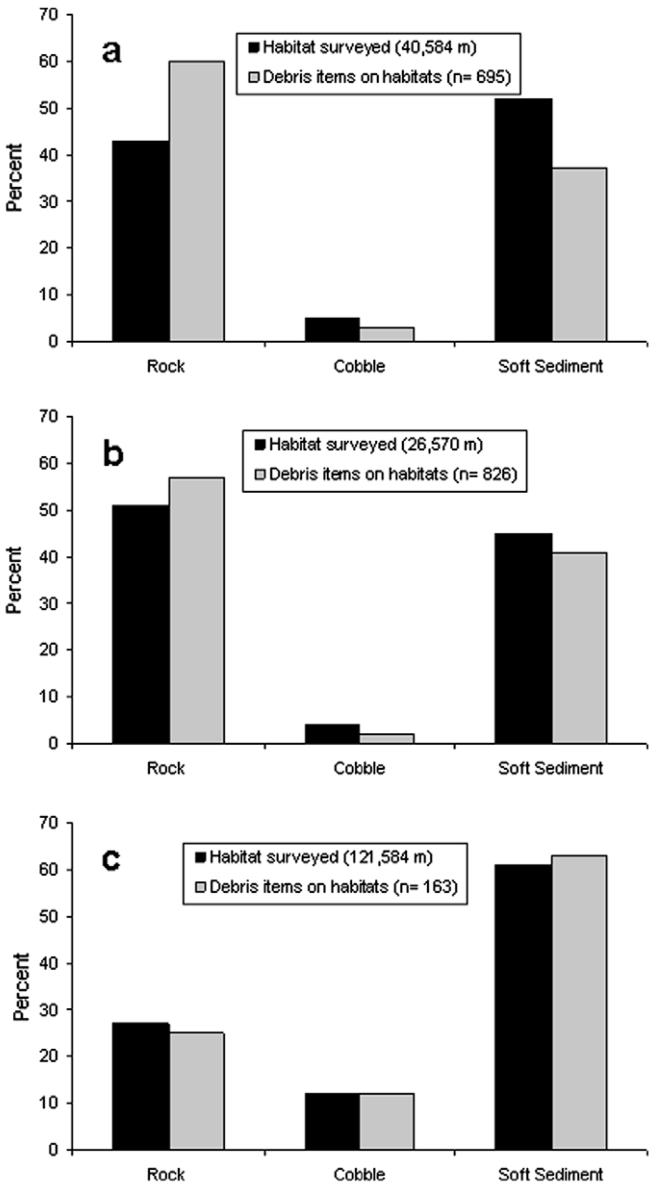

Fig. 3. Percent occurrence of habitat (seafloor substratum types) on which debris was located, relative to total amount of habitat types surveyed using the *Delta* submersible: (a) central California surveys in the 1990s; (b) central California surveys in 2007; (c) southern California surveys in 2002.

not be evaluated. Off southern California in 2002, two of eight nets were not ghost fishing and six could not be evaluated; one of eight traps was ghost fishing (see for example Fig. 5d), two were not, and five could not be evaluated.

Disturbance to habitat and macroinvertebrates from debris was generally low in both study areas and time periods. Off central California in the 1990s, no disturbance was detected for 90% of 702 items, some disturbance for 9% (primarily monofilament fishing line), and high disturbance for less than 1% (two monofilament lines). Similarly in 2007, no disturbance or damage to habitat was detected for 93% of 826 items, some disturbance for 54 items (7% – 52 monofilament lines and two nets), and no items were found to cause high disturbance. Off southern California, no disturbance was detected for 81% of 160 items, some disturbance for 18% (a broad assortment of fishing and maritime or coastal items), and high disturbance for 1% (two fishing nets).

Some debris items were used as habitat by fishes and large structure-forming invertebrates (Table 3). Off central California in

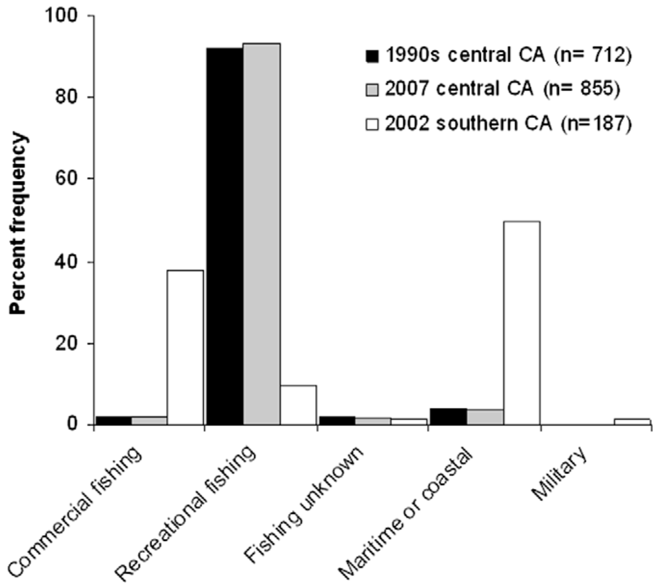

Fig. 4. Sources of debris found during deep-water (20–365 m) surveys of seafloor communities off central (1990s, 2007) and southern California (2002).

the 1990s, 13% of debris items had fishes associated with them, and 38% were associated with large structure-forming invertebrates. Similarly, off central California in 2007, less than 10% of debris items had fishes associated with them, and 30% were associated with large structure-forming invertebrates. The percentage of debris items associated with fishes and large structure-forming invertebrates off southern California also was low (7% and 14%, respectively). Fishes only associated with debris that could provide structure and cover; they did not associate with monofilament line.

4. Discussion

The densities of debris in our study can be compared with those determined by Galgani et al. (1996), who used similar methods with the manned submersible *Cyana* to survey benthic debris in the Bay of Biscaye and northwestern Mediterranean Sea. Surveys in canyons at depths 40–1448 m off Marseilles and Nice in 1995 resulted in densities from 0.3 to 11.2 items/100 m (Galgani et al., 1996), which are comparable to our densities (0–38 items/100 m) off California. Plastics also were the dominant material.

While not directly comparable to our visual surveys, Galgani et al. (1996, 2000), and June (1990) found plastics to be the most abundant material in their trawl studies of benthic debris in deep water. The density of debris caught in trawl surveys off Oregon, in the Bering Sea, and Norton Sound was 2–3500 times less than the density of debris documented by our visual surveys (Table 4) (June, 1990).

Although fishing activities were primary contributors to the debris that we surveyed in both central and southern California, there were distinct differences in the distribution, abundance, and types of debris found at the two study areas. This likely is an indication of the amount, types, and distribution of human activities that were in turn influenced by distance from port. Survey sites off central California ranged from 9 to 96 km from port. The hot spots of high density of debris and preponderance of recreational monofilament line inside Monterey Bay reflect the easy access to this area by recreational anglers. Hot spots at Italian Ledge, Monterey Canyon, and the southwestern edge of Soquel Canyon have been fished for decades and are located within 9–20 km from the

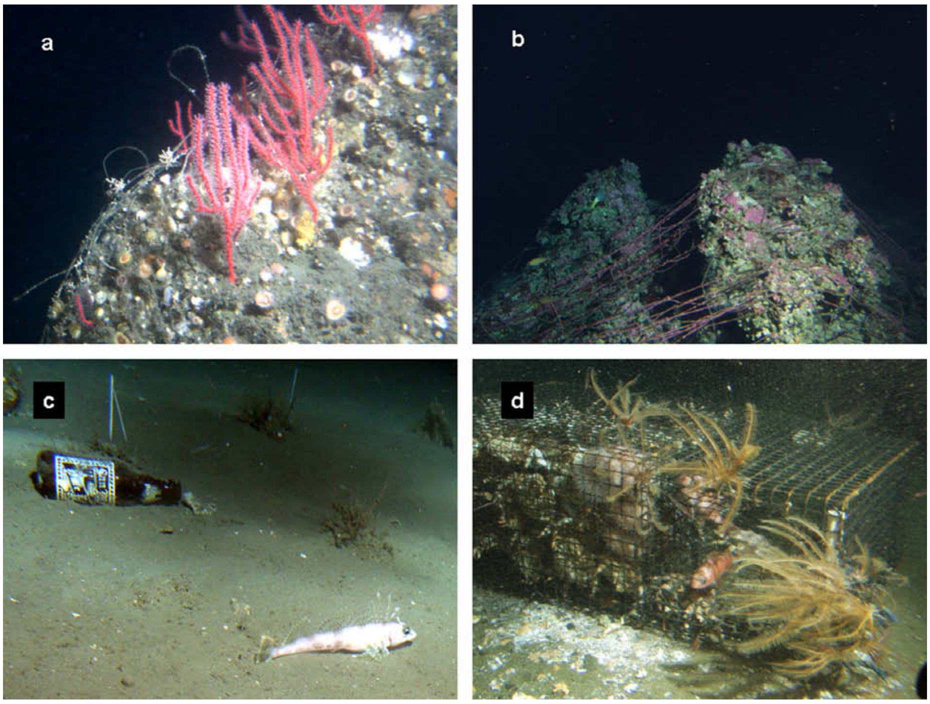

Fig. 5. Examples of debris items observed from the *Delta* submersible during deep-water surveys on the seafloor off central and southern California: (a) monofilament fishing line in gorgonian corals off central California at 95 m (photo by M. Yoklavich); (b) gill net snagged on rock off southern California at 80 m (photo by D. Schroeder); (c) beer bottle with shortspine combfish off southern California at 182 m (photo by L. Snook); (d) derelict spot prawn trap continuing to capture crabs off southern California at 247 m (photo by M. Love).

Table 1
Percent frequency and mean density (number/100 m transect) of debris types, originating from fishing activities, from deep-water surveys on the seafloor off California. ** denotes a statistically significant higher average density for 2007 than 1990s.

Fishing categories	Central CA 1990s %	Central CA 2007 %	Southern CA 2002 %
Recreational	*n* = 657 items; average density = 1.8, SE = 0.5	*n* = 794 items; average density = 3.2, SE = 0.7; **	*n* = 18 items; average density = 0.02, SE = 0.005
Monofilament	100	100	94
Fishing pole	–	–	6
Commercial	*n* = 18 items; average density = 0.05, SE = 0.01	*n* = 17 items; average density = 0.07, SE = 0.02	*n* = 72 items; average density = 0.06, SE = 0.01
Empty bait can	–	–	25
Longline	44	53	44
Net	44	24	11
Trap	11	23	11
Fishing line	–	–	8
Unknown	*n* = 11 items	*n* = 12 items	*n* = 2 items
Fishing line	91	75	100
Fishing weight	–	25	–
Fishing gear	9	–	–

fishing ports of Monterey, Moss Landing, and Santa Cruz. Debris densities fell sharply along the coast south of Monterey Bay, where there are no fishing ports. Our farthest study site, Big Creek Ecological Reserve, had virtually no debris and is located approximately 96 km from Monterey. The disproportionate occurrence of debris in rock compared to soft sediment off central California likely is due to concentrated recreational fishing effort for rockfishes (*Sebastes* spp.), which occur in complex rock habitat where monofilament line can be snagged (see example in Fig. 5a). Bauer et al. (2008) found this to be the case at Gray's Reef National Marine Sanctuary in the South Atlantic Bight, where significantly higher densities of recreational fishing and other types of debris occurred on rock ledges compared to other bottom types. These researchers attributed the higher densities to concentrated fishing effort at ledges where recreationally important fishes associate, and to the likelihood of fishing gear becoming snagged on this structurally complex habitat. Although we did not observe a change in the overall distribution, types, or sources of debris found off central California between the 1990s and 2007, the amount of debris increased over time as traditional sites continued to be fished.

Our survey sites in southern California range farther distances offshore (55–210 km from any port) than our central California sites. The density of debris at these sites off southern California was much lower than that at sites off central California, and comprised a broader array of debris sources and types. Commercial fishing and maritime or coastal activities contributed more to the debris in the area than recreational fishing activities. A pattern of decreasing debris density with distance from port was not obvious at our southern California sites. Forty-three Fathom Bank, a hot spot with the highest densities of debris, is approximately 60 km from the port of San Diego, while Hidden Reef had very little debris and is 55 km from the port of Ventura.

Table 2
Percent frequency of debris types, originating from maritime or coastal activities, from deep-water surveys on the seafloor off California. ** denotes a statistically significant higher average density for 2007 than 1990s.

Debris type	Central CA 1993–1998 % n = 24 items; average density = 0.06, SE = 0.02	Central CA 2007 % n = 30 items; average density = 0.12, SE = 0.04; one-tailed t test, $^{**}p = 0.05$	Southern CA 2002 % n = 93 items; average density = 0.08, SE = 0.01
Beverage can	25	4	29
Bottle	8	13	17
Household	4	10	13
Construction	8	3	13
Unknown can	0	0	3
Box	0	0	2
55-Gallon drum	0	0	2
Artillery	0	0	1
Anchor	0	3	1
Chain	0	0	1
Cable	8	17	2
Line	42	47	1
Hub cap	0	0	1
Tire	0	3	0
Outboard motor	4	0	0
Unknown	0	0	9
Capsule	0	0	2
Casing	0	0	1
Tank	0	0	1

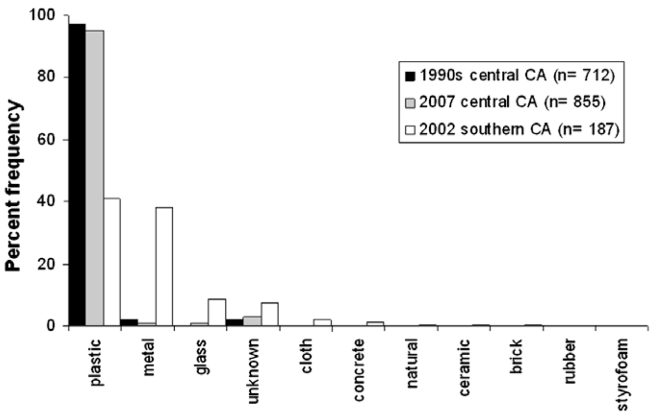

Fig. 6. Composition of marine debris found on deep-water (20–365 m) surveys on the seafloor off central (1990s, 2007) and southern California (2002).

Plastic was the most common debris material found in our study, particularly off central California where debris was dominated by monofilament fishing line. Escalating concern about marine debris has been driven by the rapid and widespread accumulation of persistent plastics over the last several decades (Barnes et al., 2009; Derraik, 2002; Goldberg, 1997; Gregory, 2009; Gregory and Andrady, 2003; Moore, 2008), which prompted the International Convention for the Prevention of Pollution from Ships (MARPOL) through its ANNEX V to prohibit the discharge of any plastics (International Conference on Marine Pollution, 1973). Solar radiation and thermal oxidation are the primary factors that influence degradation of plastics, but because these two factors are essentially missing from deep ocean environments, the rate of degradation of plastics on the seafloor is extremely low and it is unlikely that any fully degrades (Gregory and Andrady, 2003). Any degradation that does occur, however, produces plastic fragments that can be ingested by many marine organisms (Browne et al., 2008; Thompson et al., 2004).

Table 3
Associations of large structure-forming invertebrates and fishes with debris in deep-water seafloor habitats off central and southern California (% frequency of occurrence).

Organism	Central CA 1990s	Central CA 2007	Southern CA 2002
Large structure-forming invertebrate	n = 709	n = 855	n = 187
One or more on or in debris	13	28	12
One or more on, in, and near debris	12	1	2
One or more near debris	13	1	0
None	60	67	69
Unknown	2	3	17
Fishes	n = 710	n = 855	n = 187
One or more on or in debris	3	8	2
One or more on, in and near debris	1	1	3
One or more near debris	9	0	2
None	84	86	76
Unknown	3	4	18

Table 4
Estimated densities (number/km^2) of marine debris items from trawl surveys conducted by June (1990) and from visual surveys conducted in the present study from the manned submersible *Delta*.

Location	Number of debris items/km^2	Sampling method
Oregon	150	Trawl (June, 1990)
Bering Sea	8	Trawl (June, 1990)
Norton Sound	2	Trawl (June, 1990)
Central California	6900	Visual (present study)
Southern California	320	Visual (present study)

Limited information exists on the impacts of marine debris on deep benthic communities. June (1990) provided anecdotal accounts of organisms entangled or attached to debris caught during bottom trawl surveys off Oregon, the eastern Bering Sea, and Norton Sound. Stevens et al. (2000) focused only on ghost fishing of derelict crab traps near Kodiak, Alaska. From our archived video transects, we visually assessed each debris item and discerned only a few negative impacts to organisms. Two incidents of ghost fishing by derelict gear were observed over 189 km of surveyed seafloor and a variety of habitats; however, several gear items could not be evaluated for ghost fishing due to limited viewing from the videotape. We did not witness entanglement of fishes in other types of debris. The risk of entanglement to seabirds, marine mammals, and sea turtles at the depths that the debris in our study occurred (20–365 m) is likely less than has been documented elsewhere in the oceans (i.e., the shoreline, surface, and water column) (Laist, 1997). Although not quantified in our study, navigational hazards to the *Delta* submersible caused by debris were not uncommon, requiring the submersible pilot to change course in order to avoid entanglement by lines or nets.

We observed some physical disturbance to habitats (including common structure-forming macroinvertebrates) which was caused by debris. It is possible that we had limited ability to see disturbance from the videotape, especially when caused by monofilament line (Fig. 5a). However, from scuba surveys (which provide direct viewing of marine debris), Chiappone et al. (2005) found that less than 0.2% of the available invertebrates were affected by lost hook-and-line fishing gear, even though this gear caused 84% of the documented impacts (primarily tissue abrasion) to sponges and cnidarians.

This study provides the first quantitative assessment of marine debris and its impacts to the seafloor in deep submarine canyons and continental shelf locations off California and the US. We also demonstrate the value of archived databases and video surveys to improve our understanding of potential impacts of debris in remote deep-water areas. These locations comprise important habitats for hundreds of species of fishes and macroinvertebrates (Love et al., 2009; Tissot et al., 2006; Yoklavich et al., 2000, 2002). Debris altered the seafloor, by providing artificial habitat to demersal organisms. The majority of the debris was colonized, sometimes quite heavily, by encrusting invertebrates. The potential function of marine debris as habitat should be a consideration in any plans for debris removal, since removal can cause damage and kill organisms.

This debris, primarily plastics, will persist for many years and will likely continue to accumulate, just as we have reported off central California over 10–15 years. Future trends in human activities both on land and at sea (e.g., fishing, recreation, shipping, alternative energy projects, desalination, communication cables, oil and gas pipelines) will determine the type and magnitude of debris that continues to accumulate in deep water. Actions to prevent the introduction of debris into the marine environment are especially needed for the sake of remote habitats on the deep seafloor.

Acknowledgments

We thank the dedicated pilots of the *Delta*, and the captains and crews of the RV *Cavalier, McGaw, Pt. Sur,* and *Velero IV*. During this multi-year study, we appreciated the assistance of G. Cailliet, J. DeMarignac, J. Field, T. Laidig, R. Lea, C. Makeyev, G. Moreno, M. Nishimoto, V. O'Connell, P. Reilly, L. Sassone, L. Snook, R. Starr, and B. Tissot. This manuscript was improved by helpful comments from N. Barnea, T. Laidig, J. Mason, C. Morishige, S. Sogard, and an anonymous reviewer. Partial funding was provided by the NOAA Marine Debris Program, University of California Sea Grant (project number R/BC1), California Ocean Protection Council, California Department of Fish and Game, NOAA NMFS Offices of Habitat Conservation and Protected Resources, National Undersea Research Program (Grant numbers UAF-92-0063 and UAF-93-0036), Marine Protected Area Science Center, and David and Lucile Packard Foundation.

References

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society 364, 1985–1998.

Bauer, L.J., Kendall, M.S., Jeffrey, C.F.G., 2008. Incidence of marine debris and its relationships with benthic features in Gray's Reef National Marine Sanctuary, Southeast USA. Marine Pollution Bulletin 56, 402–413.

Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). Environmental Science and Technology 42, 5026–5031.

Chiappone, M., Dienes, H., Swanson, D.W., Miller, S.L., 2005. Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys National Marine Sanctuary. Biological Conservation 121, 221–230.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44, 842–852.

Gage, J.D., Roberts, J.M., Hartley, J.P., Humphery, J.D., 2005. Potential impacts of deep-sea trawling on the benthic ecosystem along the Northern European continental margin: a review. In: Barnes, P.W., Thomas, J.P. (Eds.), Benthic Habitats and the Effects of Fishing. American Fisheries Society Symposium, vol. 41, pp. 461–475.

Galgani, F., Souplet, A., Cadiou, Y., 1996. Accumulation of debris on the deep sea floor off the French Mediterranean coast. Marine Ecology Progress Series 142, 225–234.

Galgani, F., Leaute, J.P., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., Goraguer, H., Latrouite, D., Andral, B., Cadiou, Y., Mahe, J.C., Poulard, J.C., Nerisson, P., 2000. Litter on the sea floor along European coasts. Marine Pollution Bulletin 40, 516–527.

Galil, B.S., Golik, A., Turkay, M., 1995. Litter at the bottom of the sea: a sea bed survey in the Eastern Mediterranean. Marine Pollution Bulletin 30, 22–24.

Goldberg, E.D., 1975. Assessing potential ocean pollutants – a report of a Panel. Study Panel on Assessing Potential Ocean Pollutants. Woods Hole, Mass, Washington, D.C., USA, 1972. National Academy of Sciences – National Research Council, Washington, D.C., USA. Ocean Affairs Board, Washington, D.C., USA, p. 438.

Goldberg, E.D., 1997. Plasticizing the seafloor: an overview. Environmental Technology 18, 195–201.

Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings–entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philosophical Transactions of the Royal Society 364, 2013–2025.

Gregory, M.R., Andrady, A.L., 2003. Plastics in the marine environment. In: Andrady, A.L. (Ed.), Plastics and the Environment. John Wiley and Sons, Inc., Hoboken, New Jersey, pp. 379–401.

International Conference on Marine Pollution, 1973. Final Act of the Conference, with Attachments, including International Convention for the Prevention of Pollution from Ships, 1973 and Protocol relating to Intervention on the High Seas in cases of Marine Pollution by Substances other than Oil. London, IMO, 1974, ISBN 92-801-1026-8, pp. 122–125.

International Maritime Organization, 2008. International Maritime Organization. http://www.imo.org/About/mainframe.asp?topic_id=3. June 13.

June, J.A., 1990. Type, source, and abundance of trawl-caught marine debris off Oregon, in the eastern Bering Sea, and in Norton Sound in 1988. In: Shomura, R.S., Godfrey, M.L. (Eds.), Proceedings of the Second International Conference on Marine Debris, NOAA Technical Memo NMFS-SWF-SC-154, pp. 279–301.

Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris – Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 99–139.

Love, M.S., Yoklavich, M., Schroeder, D.M., 2009. Demersal fish assemblages in the Southern California Bight based on visual surveys in deep water. Environmental Biology of Fishes 84, 55–68.

Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environmental Research 108, 131–139.

Moore, S.L., Allen, M.J., 2000. Distribution of anthropogenic and natural debris on the mainland shelf of the Southern California Bight. Marine Pollution Bulletin 40, 83–88.

National Research Council (NRC), 2009. Tackling Marine Debris in the 21st Century. National Academies Press, Washington, DC.

Ord, J.K., Getis, A., 1995. Local spatial autocorrelation statistics. Geographical Analysis 27, 287–306.

Spengler, A., Costa, M.F., 2008. Methods applied in studies of benthic marine debris. Marine Pollution Bulletin 56, 226–230.

Stevens, B.G., Vining, I., Byersdorfer, S., Donaldson, W., 2000. Ghost fishing by Tanner crab (*Chionoecetes bairdi*) pots off Kodiak, Alaska: pot density and catch per trap as determined from sidescan sonar and pot recovery data. Fishery Bulletin 98, 389–399.

Stone, R.P., Masuda, M.M., Malecha, P.W., 2005. Effects of bottom trawling on soft-sediment epibenthic communities in the Gulf of Alaska. In: Barnes, P.W., Thomas, J.P. (Eds.), Benthic Habitats and the Effects of Fishing. American Fisheries Society Symposium, vol. 41, 99, pp. 461–475.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304 (5672), 838.

Tissot, B.N., Yoklavich, M.M., Love, M.S., York, K., Amend, M., 2006. Benthic invertebrates that form habitat on deep banks off southern California, with special reference to deep sea coral. Fishery Bulletin 104, 167–181.

Yoklavich, M.M., O'Connell, V., 2008. Twenty years of research on demersal communities using the *Delta* submersible in the Northeast Pacific. In: Reynolds, J.R., Greene, H.G. (Eds.), Marine Habitat Mapping Technology for Alaska. Alaska Sea Grant College Program, University of Alaska Fairbanks. doi:10.4027/mhmta.2008.10, pp. 143–155.

Yoklavich, M.M., Greene, H.G., Cailliet, G.M., Sullivan, D.E., Lea, R.N., Love, M.S., 2000. Habitat associations of deep-water rockfishes in a submarine canyon: an example of a natural refuge. Fishery Bulletin 98, 625–641.

Yoklavich, M., Cailliet, G., Lea, R.N., Greene, H.G., Starr, R., DeMarignac, J., Field, J., 2002. Deepwater habitat and fish resources associated with the Big Creek Marine Ecological Reserve. CalCOFI Report 43, 120–140.

Yoklavich, M.M., Love, M.S., Forney, K.A., 2007. A fishery-independent assessment of an overfished rockfish stock, cowcod (*Sebastes levis*), using direct observations from an occupied submersible. Canadian Journal of Fisheries and Aquatic Sciences 64, 1795–1804.