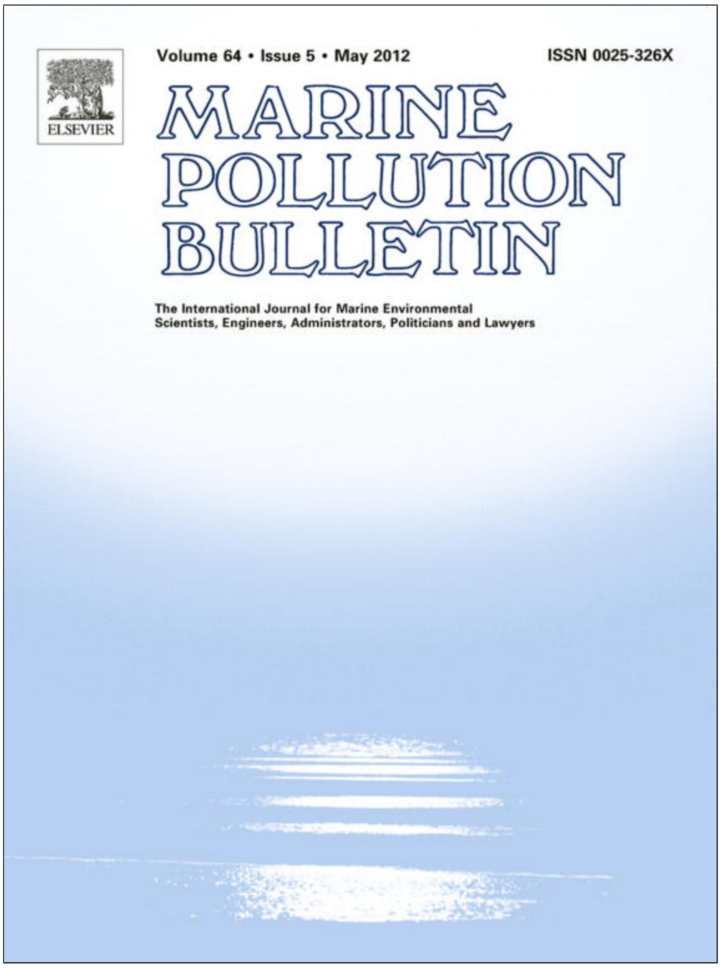
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Anthropogenic "Litter" and macrophyte detritus in the deep Northern Gulf of Mexico

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ABSTRACT

A deep-sea trawl survey of the Northern Gulf of Mexico has documented the abundance and diversity of human-generated litter and natural detrital plant material, from the outer margin of the continental shelf out to the Sigsbee abyssal plain. Plastics were the most frequently encountered type of material. Litter and debris were encountered more frequently in the eastern than in the western GoM. Land-derived plant material was located primarily within the head of the Mississippi Canyon, whereas ocean-derived plant material was spread evenly throughout the NE GoM. Human discards were principally from ships offshore. Some of the material was contained in metal cans that sank to the sea floor, probably in order to conform to international agreements that prohibit disposal of toxic material and plastics. The Mississippi Canyon was a focal point for litter, perhaps due to topography, currents or proximity to shipping lanes.

1. Introduction

The presence of human-generated litter or trash in the open ocean and along numerous beaches has been recorded for several decades (Miller and Jones, 2003). It is assumed to be a serious environmental threat to some marine life (Gregory, 2009) as well as an annoyance to humans (Barnes et al., 2009). Floating material, mostly plastics (Thompson et al., 2009), is widely distributed in the Pacific (Moore et al., 2001) and the Atlantic (Carpenter and Smith, 1972). Likewise, considerable litter has been observed on or collected from the sea floor in the Mediterranean (Galgani et al., 2000, 1996), off US West Coast (Keller et al., 2010; Moore and Allen, 2000; Watters et al., 2010) and in the Bering Sea (Feder et al., 1978), ultimately, it seems, wherever one looks, from beaches out to great depths (Galgani et al., 1996; Galil et al., 1995; Ramirez-Llodra et al., 2011). Much of the near-shore debris on reefs is recreational fishing gear lost on natural seafloor obstructions (Bauer et al., 2010; Moore and Allen, 2000), although debris large enough to be a danger to navigation can be generated by large storms (Nixon and Barnea, 2010). While human-generated debris is often detrimental to marine life (Gregory, 2009; Yoshikawa and Asoh, 2004), natural debris is known to be a source of food (Menzies and Rowe, 1969; Menzies et al., 1967; Schoener and Rowe, 1970; Turner, 1973; Wolff, 1979). Marine debris altered the seafloor and may also provide shelter for demersal organisms such as fish and invertebrates (Watters et al., 2010).

A broad biological survey of the deep continental margin of the Northern Gulf of Mexico (GoM) was conducted between 2000 and 2003 (Rowe and Kennicutt, 2008, 2009). This survey included box cores, otter and beam trawls, and sea floor multi-shot photography at depths of 250–3650 m, stretching from SW Texas over to northern Florida (Fig. 1). Our traditional treatment of trawl samples on deck has been to separate the catch first into buckets of fish and invertebrates. After the first few trawls it became obvious that we needed an additional bucket for a third category: human-produced litter and fragments of natural plant debris. The purpose of this paper is to present these new data on the types and frequencies of plant and human litter on the deep-sea floor, along with some conjecture on its spatial and temporal distribution. This deep-ocean fate of litter can then be compared to that accumulating on beaches, in convergence zones of the central gyres and on reefs.

2. Methods

The sea floor megafauna and demersal fish populations were sampled with a 12.2 m otter trawl lined with 3.8 cm stretch mesh. The trawls were lowered at ca. 25–50 m/min until the wire out was ca. 3 times the depth. Once on the sea floor, the trawls were pulled at ca. 2–4 knots for 30 min for every 1 km in depth. The distance of each trawl, and thus the area covered, was determined from precise satellite fixes when the trawl landed on bottom and when

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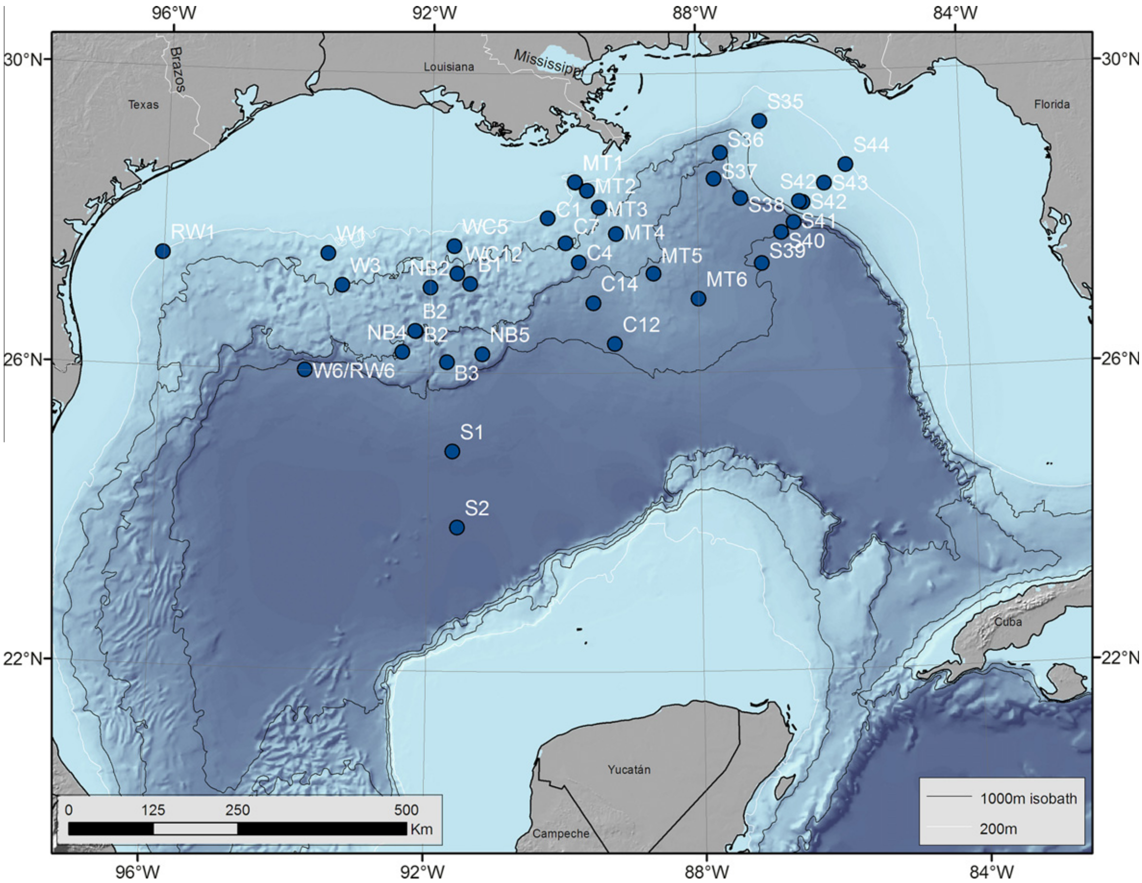

Fig. 1. Sampling locations of the DGoMB bottom trawling in summers 2000 to 2002.

it left the sea floor. These two locations were determined by a combination of tension on the trawl wire and the echo-sounder recorder (Rowe and Menzies, 1967). On recovery the samples were sorted on deck into invertebrates, fishes, anthropogenic waste (litter such as bottles, cans, paint brushes, cloth, plastics, etc.) and large fragments of plant detritus (*Sargassum* sp., bamboo, water hyacinth, wood fragments, etc.).

Three broad categories of material were: (1) anthropogenic (human-produced and discarded waste) litter or trash, (2) biogenic detrital matter and (3) lithogenic material. The detailed list of these (Table 1) illustrates the diverse spectrum of material encountered. Each composite sample of litter fractions was photographed aboard ship, listed according to type or category of material, counted and separated into either human produced litter or plant detritus. Lithogenic material was also encountered at several locations and was also separated into an additional category. Following this separation, the material was stored wet, without preservation, in 5 gallon plastic buckets. Subsamples of the plant material were frozen for later measurements of total mass, carbon and nitrogen concentrations and C and N stable isotope ratios.

Numbers of objects recovered from trawls were standardized by the sampling area (Appendix Table A1 and A2). Mean total density (ha^{-1}) was compared among parallel depth transects with Kruskal–Wallis one-way analysis of variance (ANOVA). The densities in each category and from each sample were 4th root transformed to reduce the data skewness, converted to inter-sample Bray–Curtis similarities, and then subjected to a group-average-lineage cluster analysis. Similarity profile test (SIMPROF) was conducted to identify statistical evidence of the cluster structure ($\alpha = 0.05$). Within the cluster group, the average similarities were

Table 1
'Litter' categories of deep GoM trawl sampling.

Category	
Anthropogenic	
1	Aluminum beer cans
2	Artillery shells
3	Bottle caps
4	Canvas
5	Ceramics
6	Clinkers
7	Coal
8	Cotton cloth
9	Glass
10	Glass beer bottles
11	Hooks (fish)
12	Metal containers, including paint cans
13	Metal misc.
14	Misc.
15	Missiles
16	Monofilament line
17	Nylon
18	Paint brushes
19	Paper
20	Plastic bags/wrap
21	Plastic misc.
22	Rope
23	Rubber
24	Styrofoam
25	Tape
26	Tar
Biogenic (macrophyte)	
27	Bamboo
28	Coconut husk
29	Plant pieces

(*continued on next page*)

Table 1 (*continued*)

Category	
30	*Sargassum sp.*
31	Seeds
32	Sugar cane
33	Turtle grass (*Thalassia* sp.)
34	Water hyacinth
35	Wood
Biogenic (shell and skeleton)	
36	*Crassostrea virginica* (oyster) shell
37	Vertebrate skeleton
38	Scleractinian skeleton
39	Shallow-water or pelagic mollusc shells
Lithogenic	
40	Iron stone
41	Rock

broken down to similarity percent contribution (SIMPER) of each category. These results were then mapped using Geographic Information System (GIS) across the areas sampled. The univariate analysis used R 2.14.0 (R Development Core Team 2011). The multivariate and GIS analyses employed the commercial software PRIMER 6 (Clarke and Warwick, 2001) and ESRI ArcMap 9.2.

3. Results

The total spectrum of material sampled (Fig. 2) clearly indicates that plastics were the dominant anthropogenic material, with 16 encounters adding up to a total of 42 pieces in the 40 trawls taken. If one adds the plastic bags (31 pieces in 13 encounters) and the monofilament line (131 clumps in 9 encounters), then the total was substantially higher. Aluminum cans (including beer and soft drink cans) were ranked the second most common categories (23 cans in 14 encounters). We also collected clinkers (burnt coal slag, 264 nodules in 11 encounters), presumably, disposed from the old steamships during their era of operations. *Sargassum* sp. litter was the highest ranking natural ocean-produced material (160 clumps in 22 encounters), followed by wood fragments (81 fragments in 15 encounters). There were almost twice as many categories of anthropogenic litter as natural materials. Of the natural materials, they all originated on land, in rivers or in estuaries, with the exception of the *Sargassum* sp. and turtle grass (*Thalassia testudinum*).

Examples of anthropogenic waste or litter in Fig. 3 included the one-of-a-kind Sidewinder missile (Fig. 3a) and the frequently-encountered or ubiquitous suite of beer cans (Fig. 3b) and a discarded long-line entanglement (Fig. 3c). The latter was obviously discarded on purpose because the hooks had been removed. Most of the anthropogenic wastes (91.6% of the total) were recovered from the northeastern GoM (east of Longitude 91°W), with especially high numbers at the head of Mississippi Canyon (MT1, 65.4 objects ha^{-1}), down the canyon axis, and on the periphery of the deep Mississippi sediment cone (Fig. 4a). In contrast, 9 out of 17 trawls in the northwestern GoM did not recover any trashes. The highest diversity of litters occurred on the lower slope of the Mississippi Sediment Cone (C12, MT5, and S38; 10 to 11 categories) with relatively high densities along the Mississippi Canyon axis

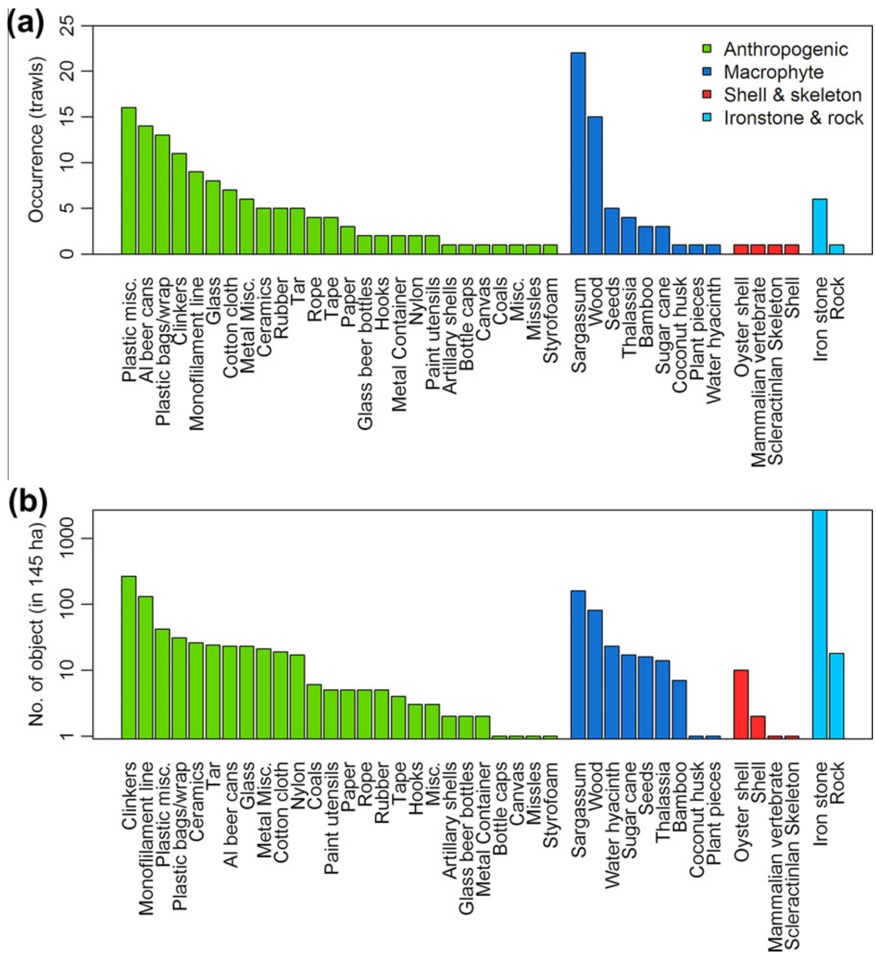

Fig. 2. (a) Frequency (number of encounters) and (b) abundance (number of objects) in the total of 40 trawls (145-ha) for each category of natural and anthropogenic materials sampled in the deep Gulf of Mexico.

Fig. 3. Examples of anthropogenic waste recovered from the DGoMB trawl sampling. (a) "Sidewinder" missile recovered from Station S44 on June 11th, 2000; (b) aluminum cans, clothes, wood fragment and *Sargassum* clumps recovered from Station MT3 on June 16, 2000; (c) abandoned fishing line recovered from Station MT1 on June 17, 2000.

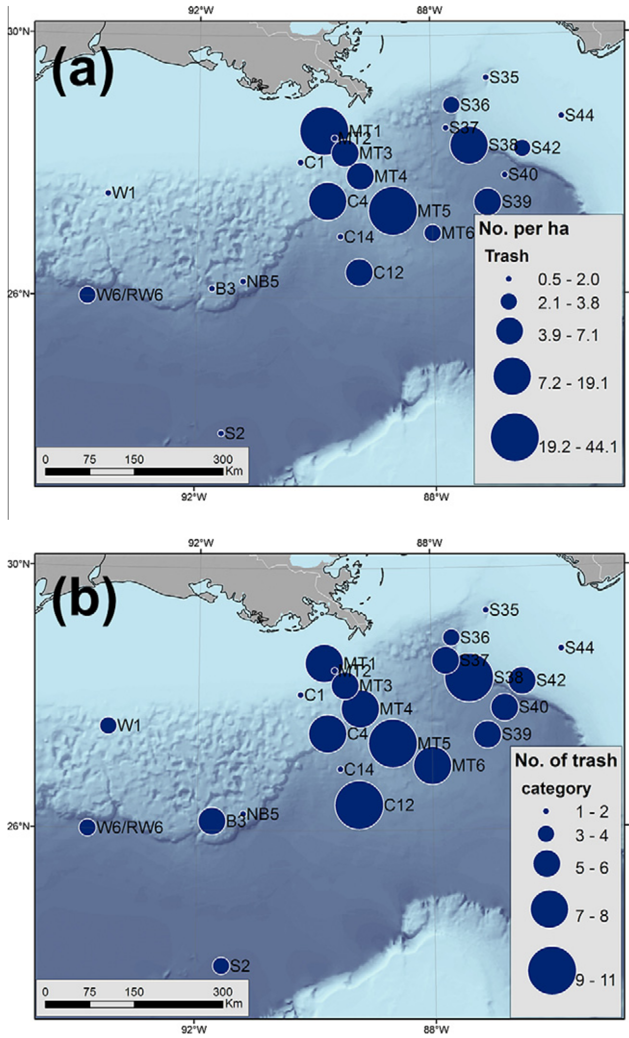

Fig. 4. Distribution of anthropogenic waste recovered from the DGoMB trawl sampling. (a) total numbers of individual pieces of 'litter' standardized to per hectare area (10^4 m^2); (b) numbers of different kinds of 'litter' at each site.

(Fig. 4b). The trash density and diversity (number of trash types) were independent of depth or distance from land (Fig. 4a and b).

Biogenic detrital fragments consisted of pieces of wood, bamboo, coconut husk, *Sargassum* sp., seeds, unidentified stems and leaves, turtle grass, and water hyacinth (*Eichhornia crassipes*). Most of the macrophyte debris (96.9% of the total) was recovered from the northeastern GoM (Fig. 5a). The total density was highest at the head of Mississippi Canyon (MT1 and MT2, 28.4 and 13.7 pieces ha^{-1}, respectively) and on the lower section of central transect (C4, 13.2 pieces ha^{-1}). The total density declined offshore along the axis of the Mississippi canyon (MT stations).

The high macrophyte density at the head of the Mississippi Canyon was mainly contributed by water hyacinth (26.1 clumps ha^{-1}, transparent color) and *Sargassum* sp. (1.1 clumps ha^{-1}, oblique lines, Fig. 5b). The densities of *Sargassum* and *Thalassia* together were higher on the mid- and lower slope with broader distribution than the land-derived plant debris (water hyacinth in Fig. 5b; wood, bamboo, sugar cane in Fig. 5c). Especially, the wood fragments appeared to be concentrated along the Mississippi Canyon and at the deeper portion of the central transect (Fig. 5c).

Ironstone is a surficial concretion first described in the GoM by Pequegnat et al. (1972). The iron precipitates at or near the sediment – water interface and the crust-like surface is often devoid of an overlying soft sediment layer in photographs of the sea floor. Its distribution in our survey conformed to that described in previous studies. Highest densities were found in the deep Mississippi Canyon (MT6, 308.1 nodules ha^{-1}) and at the base of the Florida Escarpment (S39, 192.3 nodules ha^{-1}) east of the Mississippi Sediment Fan (Fig 5d). The densities declined with distances away from the MT6 and S39 with a total of 12.1, 17, 8.4 nodules being recovered at MT5, S40, and MT4, respectively. The lowest density of ironstone was found at Site B3 (0.7 nodules ha^{-1}, Fig. 5d).

Total densities of anthropogenic wastes were significantly different among the parallel depth transects (Kruskal–Wallis test, $x^2 = 18.9$, $df = 4$, $p < 0.001$, Fig. 5a); however, the density was only significantly higher at the MT transect (21.1 ± 24.06 objects ha^{-1}, $n = 7$) than the combined transects in the northwestern GoM (0.7 ± 1.05 objects ha^{-1}, $n = 17$, multiple comparison, $p < 0.05$). The total plant debris density was also significantly different among the transects (Kruskal–Wallis test, $x^2 = 16.5$, $df = 4$, $p < 0.01$, Fig. 6b), and only the MT transect had significantly higher densities than the northwestern sites (multiple comparison, $p < 0.05$). Due to the dominance of ironstone (Fig. 4c), the Florida (S44–S39) and the Mississippi Canyon (MT) transect had the lowest total diversity (most elevated curves, Fig. 6d). Large numbers of water hyacinth recovered from Site MT1 (Fig. 5b) and wood fragments from MT2 (Fig. 5c) contributed greatly to total abundance at the beginning of the dominance curve. The central transect (C stations), on the other hand, had the highest total diversity among all transects (least elevated curve, Fig. 6d).

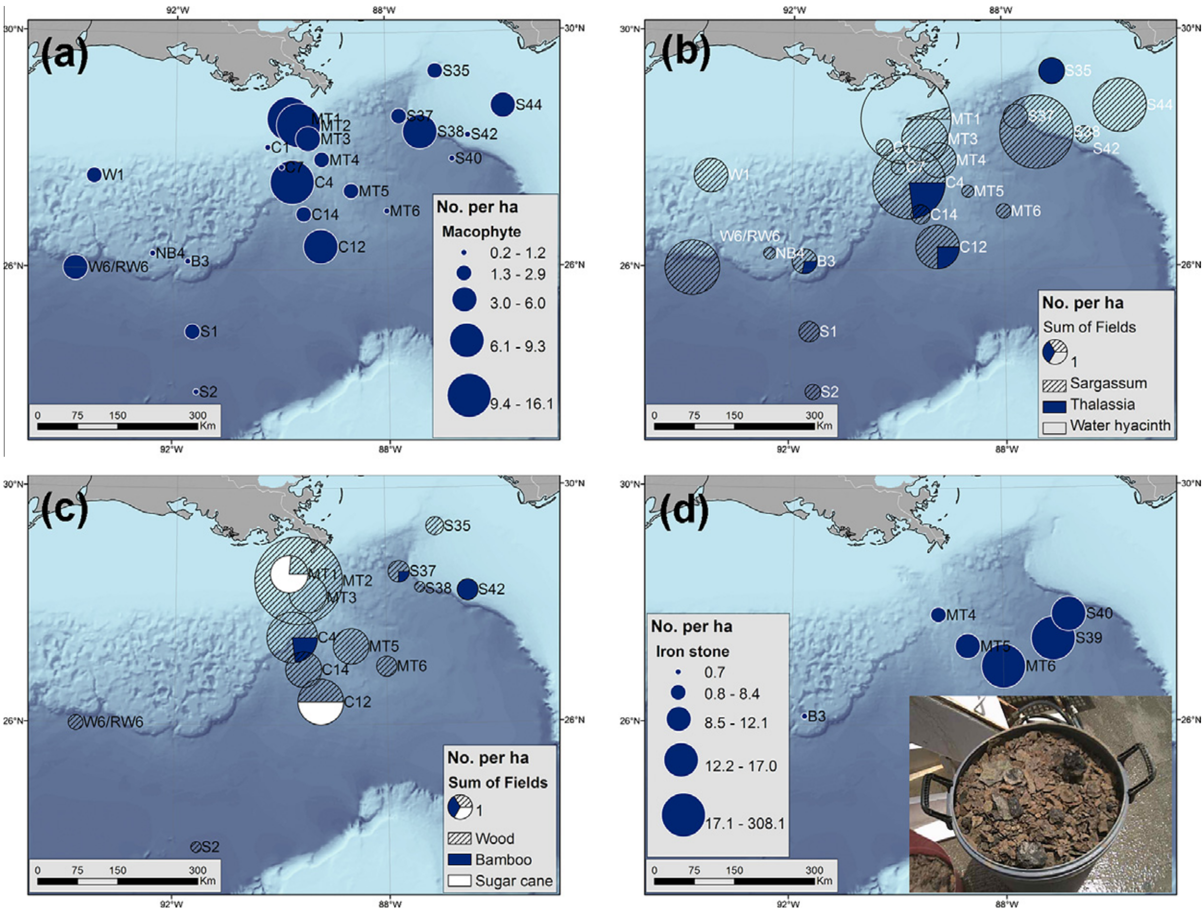

Fig. 5. Numbers of fragments of macrophytes and ironstone standardized to per hectare area. (a) Total biogenic plant debris; (b) *Sargassum* sp. (oblique lines), *Thalassia* (semi-transparent) and water hyacinths (transparent); (c) pieces of wood (oblique lines), bamboo (semi-transparent) and sugar cane (white) fragments; (d) "ironstone" sediment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

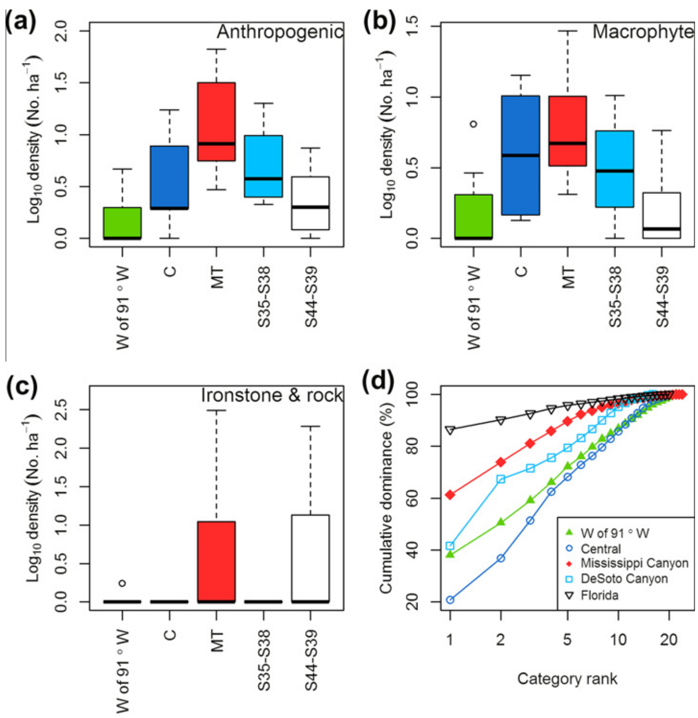

Fig. 6. Density and the cumulative dominance curve of the non-animal objects in the DGoMB trawl sampling. First three panels are box- and whisker plots on the densities of (a) anthropogenic wastes, (b) macrophyte debris, (c) ironstone and rock for each transect. The densities of individual samples are $\log_{10}(x + 1)$ transformed and transects in the northwestern GoM (west of Longitude 91°W) are lumped into a single box-and-whisker. (d) Percent cumulative abundance as functions of category ranks for each transect.

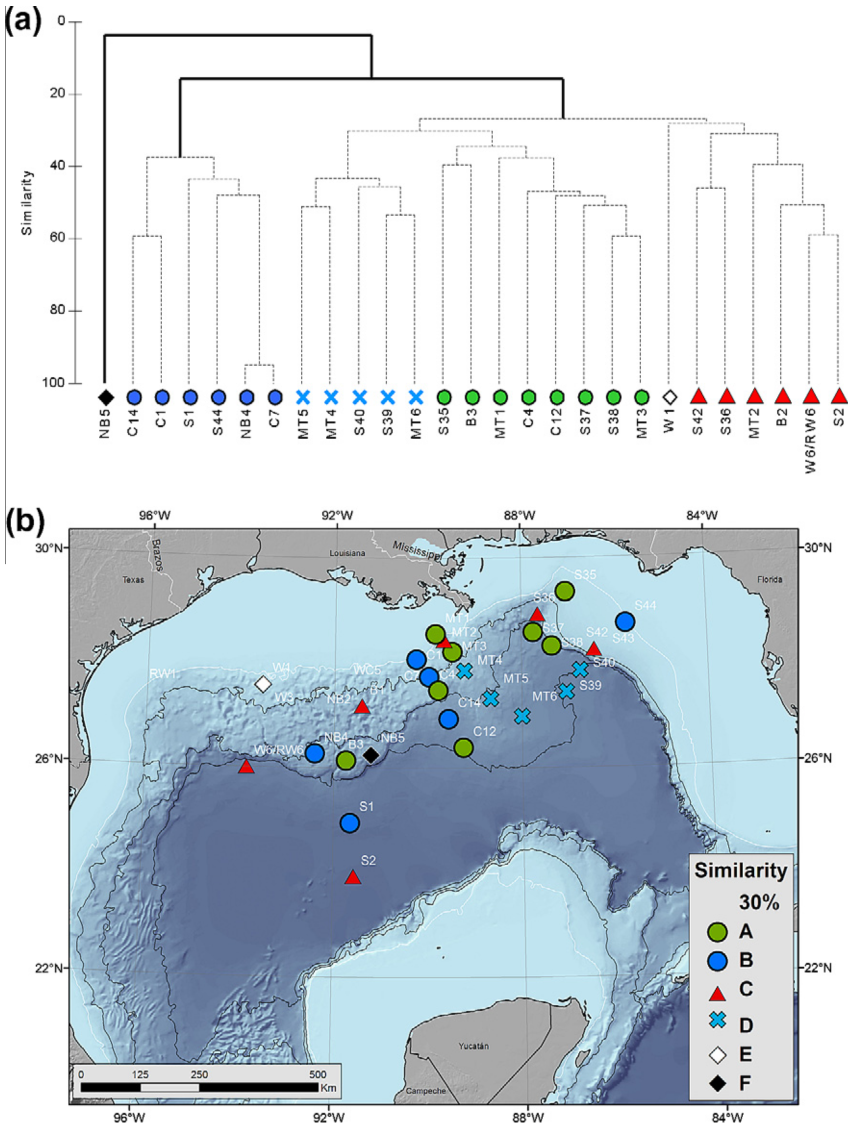

Fig. 7. Distributions of DGoMB trawl samples sharing at least 30% of Bray–Curtis similarities (all non-animal object categories included). (a) Group-average cluster analysis based on inter-sample Bray–Curtis similarities and 4th-root transformed abundance data. Solid line indicates significant structure based on SIMPROF test ($p < 0.05$). (b) Distribution of sampling sites shared at least 30% of inter-sample similarity based on group-average cluster analysis (Fig. 7a).

Cluster analysis (based on inter-sample similarities of all categories) can divide the trawl samples into six groups with at least 30% of the within-group similarities; however, only the Groups A + C + D + E, Group B, and Group F were statistically different from each other (SIMPROF, $p < 0.05$, solid lines, Fig. 7a). Except for the Group D, the distributions of homogeneous groups were widespread and not confined within specific geographic areas (Fig. 7b). In Group A, aluminum beer cans, *Sargassum* sp., and wood fragments were the most important categories and cumulatively contributing to 54.93% of the within-group average similarity (SIMPER, Fig. 8). Group B was dominated by *Sargassum* sp., which alone contributed to 95.65% of the average similarity. The lack of man-made waste and land-derived plant debris in this group (B) appears to contribute to its distinctiveness from the rest of the homogeneous groups (A + C + D + E, SIMPROF, $p < 0.05$, Fig. 7a). In Group C, miscellaneous plastics, clinkers, and wood fragments contributed to 76.46% of the average similarity. Group D was dominated by iron stones and together with plastic bags/wraps and miscellaneous plastics contributing to 69.97% of the within-group average similarity. At Site NB5 (Group F), only a metal container and metal pieces were recovered from the trawls.

4. Discussion

The preponderance of man-made wastes in the eastern GoM compared to the west may reflect shipping lain proximity as well as frequency of offshore oil and gas well platforms and fishing activity (Fig. 4a). The diversity of litter was high, but there does not appear to have been an offshore or depth trend (Fig. 4a and b). The litter was just as diverse at the deep sites as near shore. The MT sites were located in the axis (MT1–4) of the large Mississippi Canyon or offshore where material moving down the canyon is being deposited onto the Mississippi sediment fan (MT5, 6 and C12). The down-canyon transport likely associates with strong near-bottom currents and turbidity flows (Twichell, 2011). Especially, during the passage of a hurricane, the maximum current speed has been reported to reach up to 68 cm s^{-1} with 70 to 130-fold increasing of sedimentation in the upper Mississippi

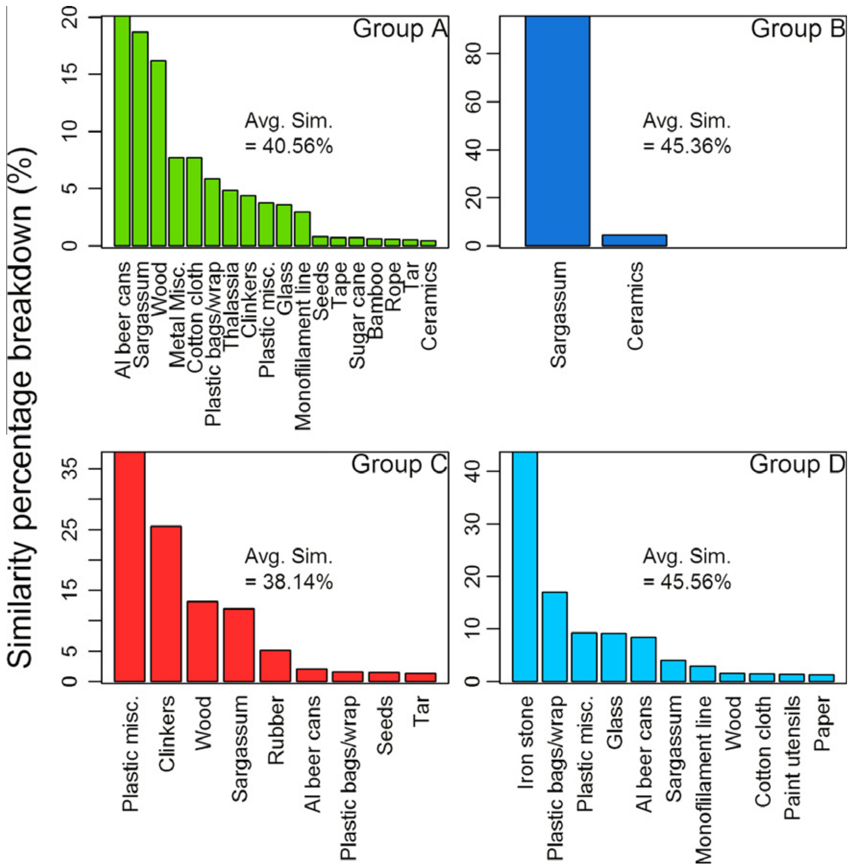

Fig. 8. Characteristic categories in each homogeneous group shared at least 30% inter-sample similarities. The groups are defined by cluster analysis (Fig. 7a). The average inter-sample similarities in each group were broken down to similarity percentage (SIMPER) contribution of each object category. Vertical bar shows the contribution of each category up to 100% of cumulative contribution in each group. The object categories with high contribution are considered as characteristic categories.

Canyon (Ross et al., 2009). Although no study has yet to demonstrate the movements of marine debris, it is reasonable to assume the frequent passages of hurricanes in the GoM may affect the distribution of the marine debris in the Mississippi Canyon and Fan. It may also be that the canyon geomorphology tends to focus and thus accumulate material that has been discarded at sea (Galgani et al., 1996; Mordecai et al., 2011). The Sidewinder missile (Fig. 3a) was probably released in training missions from the Naval Air Station in Pensacola, FL, located to the NNW of where the object was trawled up. The white pencil-shaped objects being pointed to on the missile's fin in Fig. 3a are calcium carbonate tubes constructed by serpulid polychaete worms. Their presence and size suggest that the missile had been on the sea floor for months or more. Other evidences also suggest that marine debris can provide new habitats for demersal organisms. For example, we found sea anemones attached to an onion sack and deep-sea hermit crabs (family Parapaguridae) inhabiting shells of *Janthina* sp., a pelagic mollusk that lives in surface waters. We also found deep-sea anemones (family Hormathiidae) and stalked barnacles (family Scalpellidae) attached to rocks.

Biogenic plant debris can be separated into that coming from land, rivers or estuaries and pelagic *Sargassum* sp. The latter was widespread in many deep samples, but the shore-derived material was encountered principally near the upper continental margin, especially in the head of the Mississippi Canyon (MT1). Although the canyon is not connected to the current mouth of the Mississippi River (Fig. 1), the westward flow the river plume during most of the year can transport land-derived material to the canyon. Note however that the contents of the samples can change substantially at the same site but in different years. MT1 trawls (canyon head) contained a lot of water hyacinth one year (2001) but not the other (2000). Although the water hyacinth was obviously transported to the site by the Mississippi River plume, we can give no reason why this was greater in 2001 than in 2000. Both trawls were made in the May/June period.

The land-derived litter (man-made wastes and macrophytes) appears to control the composition of materials recovered in the trawls, because the oceanic plant debris (*Sagassum* and *Thalassia*) was more evenly distributed throughout our sampling area (Fig. 5b). This may explain why SIMPROF did not detect statistical difference in samples where the land-derived litter is present (Group A + C + D + E, Fig. 7). Regardless of source, the plant detritus probably serves as a food source to the sediment community at all depths (Menzies and Rowe, 1969; Menzies et al., 1967; Schoener and Rowe, 1970; Turner, 1973; Wolff, 1979), and thus is consumed at some as yet unknown rate.

It is worth noting that much of the litter or human debris was not apparently scattered about the bottom but rather was containerized in metal cans. Had the material been scattered about, we would have found the items as individual pieces, many of which would have floated on the surface. The 5-gallon cans constructed of ferrous metal had closed lids but were heavy enough that they would eventually if not immediately sink to the bottom. International agreements (Marpol Annex V) list what ship-generated solid wastes may be dumped at sea. Paraphrasing Appendix L (South Atlantic Fishery Management Council, 1998), discarding plastic material (ropes, fishing line, nets, bags, etc.) at sea is completely prohibited. However, non-plastic 'floating dunnage, packing material, etc.' can be released but not within 25 miles of land. Also, paper, rags, glass, metal bottles, etc., can be released at sea but not within 12 miles of land. Likewise paper, rags, glass, etc. that have been broken into pieces less than 2.5 cm in size can be discarded at sea, but not within 3 miles of land. Offshore oil and gas platforms are prohibited from disposing of anything solid at sea. There is no direct evidence in our survey that they had been. Getting around the international regulations would be solved by putting floatable wastes together in cans and sinking them at sea. This strategy may be why so much of the 'prohibited' material we sampled was containerized.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marpolbul.2012.02.015.

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