Sedimentary records of microplastic pollution from coastal Louisiana and their environmental implications

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Abstract

Microplastics are a growing concern in the natural environment as plastic production and improper disposal have greatly increased since the first widespread use of plastic in 1950. Previous studies have investigated the amount of plastic found within organisms, the water column, and surface sediments, but few studies are available that investigate microplastics within the sedimentary column. This study seeks to determine the abundance of microplastics and their rate of deposition in two coastal Louisiana estuaries (Bay Champagne and Little Lake) that are influenced by the petroleum, shipping, and commercial fishing industries. Samples from two short sediment cores were treated for microplastic analysis following NOAA removal techniques. Microplastics were identified visually and confirmed using FTIR spectroscopy. Three morphotypes of microplastic were found throughout the sediment column in the cores (fibers, fragments, and sheets), with a high concentration near the surface and a major decrease downcore. Of the two sites, Little Lake had a much higher total abundance of microplastics than Bay Champagne, likely due to its proximity to New Orleans and the active commercial fishery. Interestingly, both sites had trace amounts of microplastic in basal samples, in sediment much older than 1950. Their presence is likely attributable to bioturbation by burrowing organisms, although sediment reworking by high energy disturbance events (i.e., hurricanes) or human activity is also possible. Microplastic presence within these highly productive estuarine waters is a major ecological issue and understanding the possible sources and sinks of microplastics is critical in addressing this growing problem of environmental pollution.

Keywords Microplastic · Sedimentary record · Coastal wetlands · Plastic pollution · Louisiana

Introduction

Global production of plastics in 2018 exceeded 350 million tons, with annual production amounts increasing between 5% and 8.4% each year leading up to 2018 (Brahney et al. 2020; Cunningham et al. 2020). The current annual production rate of plastics is over 200 times the initial rate from 1950 (Yu et al. 2018; Fig. 1). Of the plastics that are produced, about half are considered single use, meaning they are discarded after their first use (Matsuguma et al. 2017; Schnurr et al. 2018). These include products such as plastic bags, microbeads, plastic cutlery, and straws (Matsuguma et al. 2017; Schnurr et al. 2018). Of all the plastics ever produced, 21% have been recycled or incinerated, while the remaining 79% are either in landfills or have been discarded in the natural world (Geyer et al. 2017).

Plastics that are exposed to weathering elements after improper disposal and subsequent break down (e.g., through UV, hydrolysis, biodegradation, etc.) form microplastics, which can persist for hundreds of thousands of years in the environment (Matsuguma et al. 2017; Andrady 2011). As increasing amounts of single-use plastics make their way into the environment and degrade, quantities of microplastics being shed will also increase at similar rates (Cózar et al. 2014; Li et al. 2015). Plastic pollution is considered to be a "microplastic" if it is less than 5 mm in size (Turra et al. 2014; Masura et al. 2015; Di Mauro et al. 2017). Microplastics can be divided into categories based on several characteristics including polymer type (polyethylene, polypropylene, polystyrene, and polyester, among others), morphotype (fibers, fragments, and pellets), and their range of colors

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Fig. 1 Annual global production (a) and cumulative global production (b) of plastics. Data from Geyer et al. 2017 ▶

(most commonly black, red, blue, white, and clear) (Cózar et al. 2014; Li et al. 2015; Xue et al. 2020).

In 2014, it was estimated that 5.25 trillion pieces of plastic, weighing nearly 270 thousand tons, were located on the surface of the world's oceans (Eriksen et al. 2014). It is important to note that this estimation is only for the amount of plastics on the *surface* of the oceans; it does not account for terrestrial microplastics, nor those that are present along the shoreline, suspended within the water column, or on and within the seabed. In fact, it is estimated that plastics on the ocean surface account for only 0.1% of the annual worldwide production of plastics (Cózar et al. 2014). Therefore, it stands to reason that the majority of plastic in the oceans reside elsewhere, likely sequestered in sediment found in the deep ocean and along the shoreline (Cózar et al. 2014). Additionally, according to Eriksen et al. (2014), the observed abundance of microplastics within oceanic water samples were much less than the expected abundance (determined using a fragmentation model), so this missing fraction must be located somewhere other than in the surface ocean (Cózar et al. 2014). Because of the underrepresentation of microplastics in surface waters, a size selective sink, wherein smaller particles are fragmented and precipitate into ocean and coastal sediments, has been proposed as a likely ultimate fate for the majority of oceangoing microplastics (Thornton and Jackson 1998; Hidalgo-Ruz and Thiel 2013; Cózar et al. 2014; Eriksen et al. 2014; Zhang 2017; Xue et al. 2020).

In addition to being delivered through marine sources (e.g., coastal flooding and tidal movement), microplastics can be washed from terrestrial environments into the coastal environment by freshwater flooding and stormwater discharge (Zhang 2017; Xue et al. 2020). For example, following a storm in California, microplastics in surface waters (top 15 cm) and bottom sediments of the nearshore ocean were detected at a much higher density than the background rates (18 pieces/m^3 versus 0.5 pieces/m^3 and 11 pieces/m^3 versus 0.75 pieces/m^3, respectively) as well as being deposited further away from the river mouth than average (Lattin et al. 2004). After initial deposition in surface sediments, bioturbation, anthropogenic processes, and high energy oceanographic events such as hurricanes and winter storms can act as mechanisms by which microplastics are fragmented and buried within sediment, up to 2 m deep (Turra et al. 2014; Dellapenna et al. 2006; Xue et al. 2020).

Few studies have been completed on the topic of microplastic abundance in three dimensions (Turra et al. 2014; Matsuguma et al. 2017; Xue et al. 2020). While most sedimentary microplastic studies are focused on surface sediments (sediment up to 5.5 cm depth), it is estimated that storage of microplastics in downcore sediment could total

a) Annual Global Production

b) Cumulative Global Production
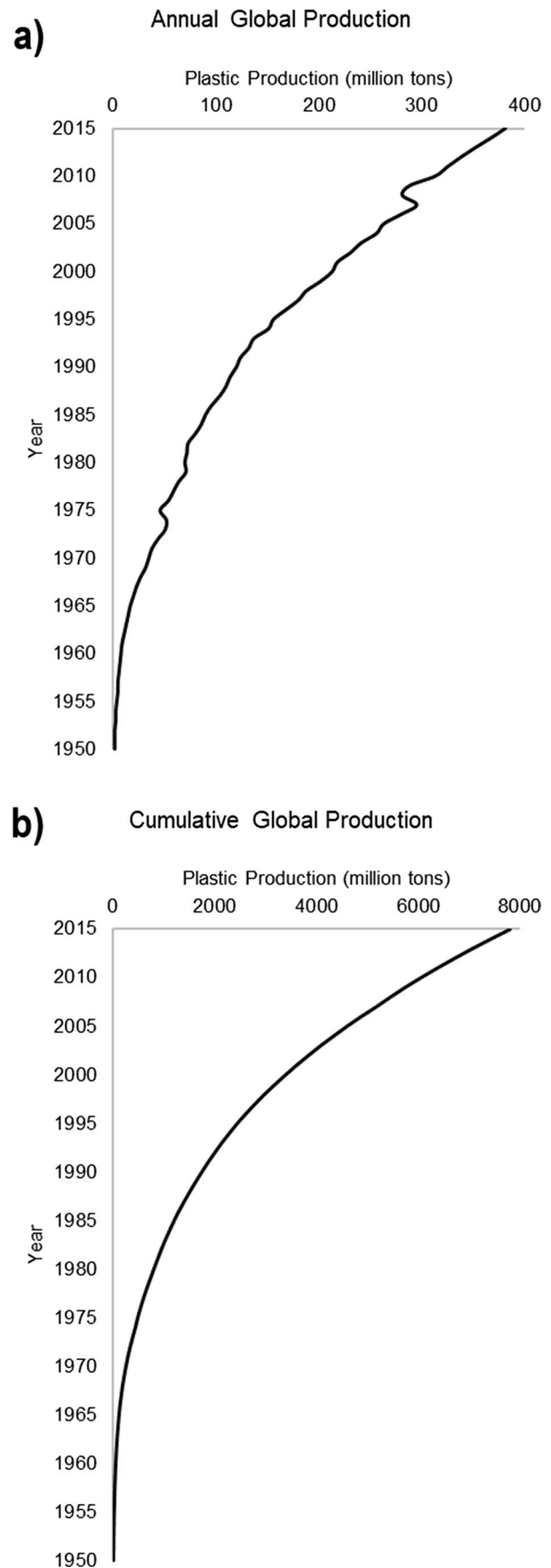
up to 5 times the amount seen in surface samples (Turra et al. 2014; Xue et al. 2020). If microplastics truly are precipitated from the water column and deposited in a sedimentary sink, then a coastal downcore study can be used to determine if coastal sediments are an important portion of the sink, as well as determining the rate of microplastics sedimentation since their initial widespread use in 1950 (Cózar et al. 2014; Geyer et al. 2017; Turra et al. 2014; Yu et al. 2018; Xue et al. 2020).

Materials and methods

Study region

Previous studies that investigate microplastic in the Gulf of Mexico focus on coastal (marine and terrestrial) surface sediments, water, and within fish and shellfish (Yu et al. 2018; Wessel et al. 2016; Phillips and Bonner 2015). Downcore sediments are potentially an important and understudied microplastic sink and archive of microplastic pollution in the region (Cózar et al. 2014). Louisiana coastal waters have historically been highly trafficked by commercial vessels because of the abundance of fish, shellfish, and petroleum products, as well as ease of bulk transportation through the Mississippi River and its distributaries, thus providing an outstanding opportunity for a downcore microplastic pollution study (Adams et al. 2004).

Louisiana has the fifth highest shoreline mileage among U.S. states (7,721 miles of shoreline) and the largest amount of wetlands in the United States, nearly three million acres of which are coastal (NOAA Office for Coastal Management 2020; Jessen 2006). The Louisiana coast is also home to numerous energy harvesting and refining plants, a large shipping industry (with three ports ranking among the top fifteen worldwide), and extremely productive commercial and recreational fisheries (Adams et al. 2004; Cieslak 2005; Jessen 2006). Each of these important Louisiana industries are major contributors to microplastics within the world's oceans (Browne 2015). As plastics have even been found to reach shorelines of some of the most remote islands in the world (Barnes 2005; Bergmann et al. 2015), it stands to reason that the highly trafficked Louisiana coast will have high amounts of marine plastic litter in and on its coastal wetlands, in particular, around Port Fourchon.

Port Fourchon (located at the mouth of Bayou Lafourche) is a multi-use port that serves as a service center for offshore oil and gas facilities and is the only major Louisiana port that is located directly on the Gulf of Mexico (Cieslak 2005; Hughes et al. 2002). The port is flanked by another petroleum industry facility, the Louisiana Offshore Oil Port (LOOP), only 21 miles away (Hughes et al. 2002). While not as busy as Port Fourchon, the LOOP still handles up

Fig. 2 Satellite image of locations of the two study sites within southern Louisiana: Bay Champagne (BC-C) and Little Lake (LLSWMA-4). Image from Google Earth

Table 1 Coordinates of cores used in this study

Core ID	Latitude	Longitude
BC-C (Bay Champagne)	29°70′0.70″N	90°10′49.00″W
LLSWMA-4 (Little Lake)	29°65′57.88″N	90°5′2.42″W

to 1.2 million barrels of crude oil daily (about 10% of all U.S. crude oil imports yearly) and accommodates the shipping industry that delivers it (Hughes et al. 2002). The other major industry in and around Port Fourchon is the commercial fishery, with 8% of Louisiana's sizeable seafood harvest occurring in the Bayou Lafourche area (Hughes et al. 2002). Because each of these two industries by their very nature produce a certain level of pollution in the coastal region (e.g., fishing nets sloughing off pieces and the storage and transportation of petroleum in plastic barrels), microplastic pollution will almost certainly be present in the waters and shorelines surrounding these industrial areas. Additionally, this means microplastic will also likely be present downcore (Xue et al. 2020).

The remarkable archival capability of the abundant marshland in coastal Louisiana, as well as its frequent flooding, hurricane strikes, and heavy commercial use make it an ideal location for studying the deposition of microplastics in the region (Watson et al. 2017; NOAA Office for Coastal Management 2021; Geyer et al. 2017).

Study sites

The study sites, Bay Champagne and Little Lake, were chosen because these wetlands are continuously flooded or submerged, having low velocity water movement, and being in close general proximity to Port Fourchon, Bayou Lafourche, and the surrounding industrial facilities. Two cores, one coastal (BC-C) and one somewhat more inland

(LLSWMA-4), were taken to determine the difference in microplastic morphotypes and deposition rates in two areas (Fig. 2; Table 1).

Core BC-C was a 72 cm long aluminum push core collected in November 2016 in open water within Bay Champagne, a semi-circular coastal lake (average depth of about 2 m) located just southeast of Port Fourchon within the Caminada-Moreau Headland (Fig. 3a; Liu et al. 2011; Dietz et al. 2018; Rodrigues et al. 2021). This lake is surrounded by black mangroves (*Avicennia germinans*), salt marsh vegetation, and a narrow barrier beach with an approximately 2 m high dune system (Cohen et al. 2021). The primary depositional processes in the lake are from both fluvial and marine sources (Dietz et al. 2021). While Bay Champagne is separated from the Gulf of Mexico (GOM) by only a narrow beach, there is not a consistent direct connection to the GOM (Dietz et al. 2018). Rather, the closest consistent connection to the GOM is west of Port Fourchon, roughly 6.5 km away from the lake through dredged navigation channels. However, the site is frequently affected by hurricanes and the related storm surge induced overwash and flooding, which may cut ephemeral channels through the beach, allowing for short-term water and sediment exchanges with the GOM (Dietz et al. 2018, 2021). Additionally, a bi-modal

depositional mechanism (via storm surge and freshwater flooding) likely drives sedimentation in Bay Champagne during a hurricane (Dietz et al. 2021). This mechanism could deliver higher concentrations of both terrestrial and oceangoing microplastic into the lagoon than during normal conditions. Typical water characteristics in normal conditions include a microtidal range (< 0.4 m), minimal water movement, and a brackish environment with freshwater input primarily from Bayou Lafourche to the north and local precipitation (Dietz et al. 2018, 2021).

Core LLSWMA-4 was a 165 cm long aluminum push core taken from the edge of a marsh at the southern end of Little Lake (average depth of about 1.5 m) within the Barataria Basin (Fig. 3b) (Bass and Turner 1997). Little Lake is a microtidally (< 0.4 m) influenced brackish lake approximately 40 km northeast of Bay Champagne, is 25 km from the nearest inlet to the GOM, has an average depth slightly less than 2 m, and is surrounded by at least 95% salt marsh vegetation (Pardue et al. 1992; Bass and Turner 1997; United States Geological Survey 2021). Due to the natural levees around the Mississippi River, the main source of freshwater in the Barataria Basin is rainfall, with some riverine input from the Barataria Waterway (primarily from the manmade Harvey and Algiers Drainage Canals from the Mississippi River near New Orleans) (Coastal Wetlands Planning, Protection, and Restoration Act, [CWPPRA] n.d.; United States Army Corps of Engineers 2013; Ryu et al. 2021). The Barataria Basin includes multiple major navigation routes for the oil and gas, sulfur, and commercial and recreational fisheries (CWPPRA n.d.) and is adjacent to Bayou Lafourche, one of the most commercially important fisheries in Louisiana, primarily targeting shrimp and crabs using bottom trawl nets made of plastic lines (Curole 1991).

Field methods

Sites were selected based on satellite images through Google Earth before attempting field work. Sites were carefully approached by boat, ensuring that coring locations and surface sediments were not disturbed. Each core was taken using push coring methods as outlined in Ginsburg and Lloyd (1956), capped, sealed with rubber caps and tape, and then transported to the Global Change and Coastal Paleoecology Lab at LSU's campus in Baton Rouge, Louisiana.

Laboratory methods

Loss-on-ignition (LOI) analysis was conducted at 1-cm intervals downcore following the procedure described by Liu and Fearn (2000). Core BC-C was sampled in its entirety (72 cm) and core LLSWMA-4 was sampled through 90 cm, beyond the expected 1950 CE sediment horizon. Sediment samples were sequentially heated at

Fig. 3 Close-up satellite photos of locations of cores BC-C (a) and LLSWMA-4 (b). Images from Google Earth

105 °C for 24 h, 550 °C for 4 h, and 1000 °C for 4 h to determine the water content, organic matter content, and carbonate content, respectively (Liu and Fearn 2000; Heiri et al. 2001). X-ray fluorescence (XRF) analysis was conducted at 1-cm intervals using an Olympus Innov-X handheld analyzer to determine chemical concentrations within the sediment. These two processes were used to determine the presence of any potential overwash layers in the cores (Liu and Fearn 1993; 2000; Culligan 2018; Ryu et al. 2021; Yao et al. 2018) and to reflect the provenance of the sediments (i.e., marine versus terrestrial) (Liu et al. 2015; McCloskey et al. 2018; Yao et al. 2020). Overwash layers or marine sediments are generally characterized by increased amounts of the elements Sulfur (S), Chlorine (Cl), Calcium (Ca), and Strontium (Sr), whereas fluvial or terrestrial sediments are characterized by increased amounts of Titanium (Ti) and Iron (Fe). The ratios Cl/Br and Ca/Ti can also be used to indicate sediment source, as a higher ratio generally suggests more marine input to the sediment layer (Yao et al. 2018, 2020).

Microplastic identification

To separate microplastics from all organic material and other sediments, the procedure outlined by Masura et al. (2015) was followed. To have enough sediment to provide a count-able sample of microplastics, samples were taken at a 3-cm resolution (roughly 66 cubic centimeters), then dried. Each sample was disaggregated with 5.5 g/L potassium metaphosphate for one hour, then sieved through a 0.3 mm sieve and dried. A density separation technique was followed next for each sample, using the heavy liquid zinc bromide diluted to a density of 1.6 g/ml. The supernatant and all floating particles were collected and dried while the heavy liquid was filtered and recycled for future use. Using an iron sulfide solution (15 g/L of $FeSO_4 \cdot 7H_2O$ and 6 mL/L H_2SO_4) and 30% hydrogen peroxide, each sample was oxidized until no reaction occurred when more hydrogen peroxide was added, before finally being sieved and dried. Weights were taken after each step was completed, and samples were covered in aluminum foil to prevent any outside contamination.

Samples were observed under a dissecting microscope (AmScope Stereo Microscope) and microplastics were identified. For a particle to be counted as a microplastic, three standard rules were followed, as described in Xue et al. (2020): particles cannot be able to be torn by tweezers, they must not have any cellular or organic structures, and fibers must be equally thick throughout. This ensured that no organic material or other material visually similar to microplastic was falsely counted. Individual microplastic morphotype (e.g., fibers, fragments, and sheets), color group, and size were documented. Abundance (pieces/sample), total

abundance (pieces/core), and concentration (pieces/kg of sediment) were calculated within each core. Examples of microplastics found in the cores are seen in Fig. 4.

Fourier-transform infrared spectroscopy

Fourier-transform infrared (FTIR) spectroscopy is a non-destructive technique that identifies the chemical makeup of natural and manmade materials, including microplastics, by recording vibrational spectra which are unique to individual materials (Corcoran et al. 2009; Fan et al. 2012; Käppler et al. 2016; Cabernard et al. 2018; Yu et al. 2019). As the functional groups and chemical makeups of different polymer types of plastics have been well documented, FTIR spectroscopy is a highly successful identification technique for microplastics in sediment samples (Tagg et al. 2015).

Representative samples of microplastics were run through FTIR spectroscopy to identify polymer type and to prevent any false identifications. Due to the size restraints required by the FTIR spectroscopy technique (> 500 μm in length), two large pieces of microplastics from core LLSWMA-4 were tested—a white fragment from 12–15 cm, and a red fiber from 15–18 cm. Spectroscopic results were compared to standards from the computer library and the tested piece was determined to be composed of the polymer type (e.g., nylon, PVC) with the highest percentage match.

Results

Core BC-C

Chronology

A ^{14}C date taken from a peat layer at 65–67 cm depth returned a date of 530 cal yr BP (Dietz 2019). In addition to the ^{14}C date from core BC-C, another core (BC-64B) taken from a small pond amid a mangrove swamp behind Bay Champagne was ^{137}Cs dated and provided relative dating information on the 1950 sediment horizon in core BC-C. Core BC-64B (located approximately 100 m from core BC-C) exhibited a 1963 cesium peak at 20 cm and a 1954 cesium peak at 25 cm (Ryu 2020).

Microplastic stratigraphy

The total abundance of microplastics in core BC-C was 63 individual pieces, distributed between fibers, fragments, and sheets. No other microplastic morphotype (e.g., pellets, foam, etc.) was seen in this core. Fibers were the
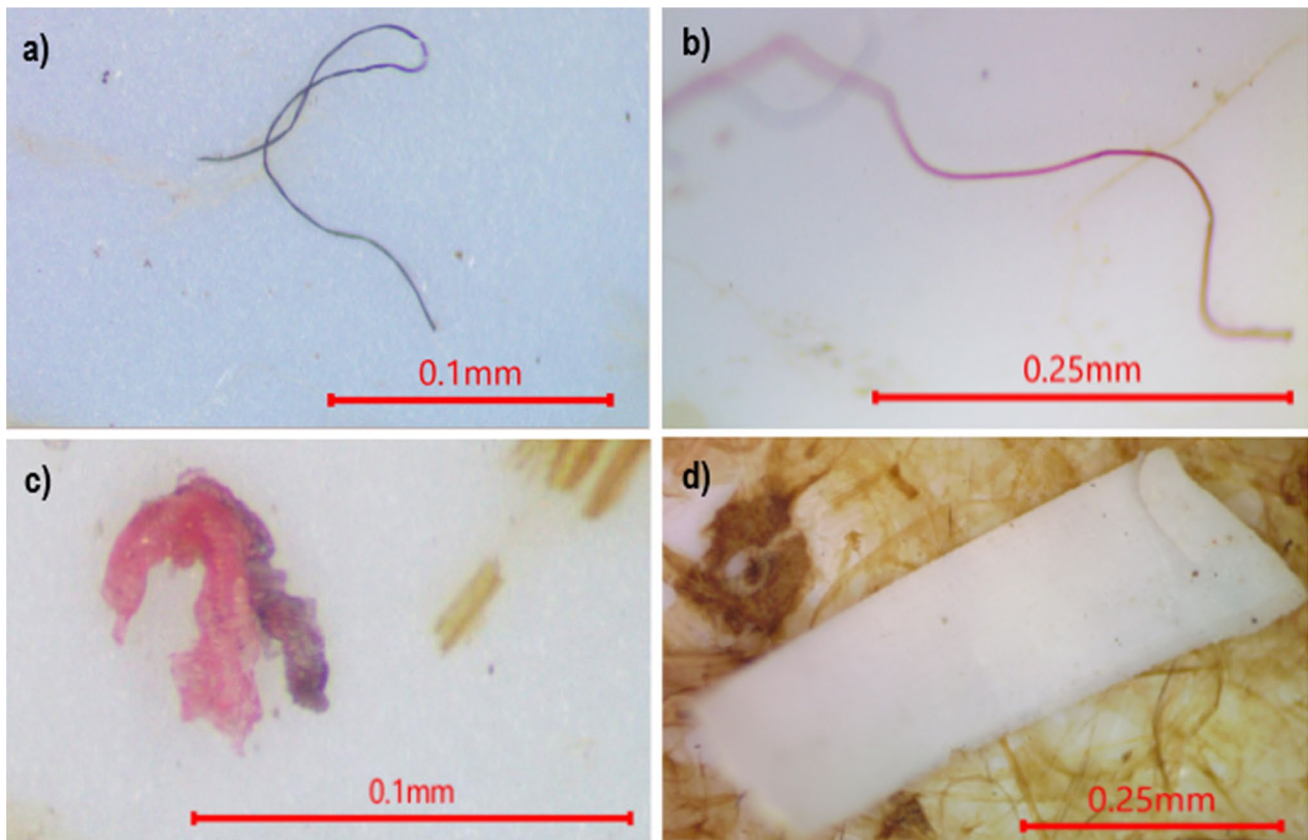
Fig. 4 Examples of microplastic morphotypes found in Core BC-C and LLSWMA. (a) and (b) are fibers and (c) and (d) are fragments

dominant microplastic morphotype (72.42%) downcore, with sheets and fragments equally abundant (11.29%) (Fig. 5a). Ten different color groups were observed within the morphotypes, with 5 types of fiber (black, blue, translucent blue, red, and clear), 3 types of fragments (clear, red, and brown), and 2 types of sheets (translucent blue and clear).

Medium size microplastics (between 0.1 mm and 0.5 mm) were the most abundant (39 total; 58.0%), followed by the small size (less than 0.1 mm; 24 total; 35.5%), and the large size (greater than 0.5 mm; 4 total; 6.5%) (Fig. 5b). The average size of all microplastic pieces was 0.19 mm.

Microplastics were present in 19 of the 23 samples analyzed and were present in the highest concentrations in the top 15 cm (Fig. 6). Vertical distribution of microplastics follows a general decreasing trend, with an average concentration of roughly 210 pieces/kg in the top 15 cm, and an average of roughly 36 pieces/kg in the bottom 15 cm. The overall average throughout the core was roughly 78 pieces/kg. Below the first two "zero count" samples at 18–21 and 21–24 cm depth, no sample reached the concentration found in the top 15 cm.

Interestingly, microplastics were found in nearly every sample in the core, even in basal samples dated to 530 cal yr BP. Thus, the presence of microplastics in sediments of pre-1950 age suggests that a post-depositional mechanism (likely bioturbation) occurred, mixing the sediment and redistributing surficial microplastics deeper into the sediment column.

While the XRF and LOI results from core BC-C do not exhibit any pronounced change in elemental concentrations and sediment makeup near the top of the core, Dietz (2019) determined that a likely flooding event occurred around 7 cm by observing a sharp decrease in $\delta^{13}C$ isotopic values at that level. This coincides with a resurgence of microplastic concentration (in sample 6–9) amid a decreasing trend, which may be a result of excessive fluvial flooding transporting microplastics from the adjacent marshes into Bay Champagne. The presence of sedimentological characteristics consistent with a flood event at 7 cm depth and the concurrent increase in microplastics abundance provides sedimentological evidence for increased microplastic discharge after storms and floods (Lattin et al. 2004; Zhang 2017; Xue et al. 2020).
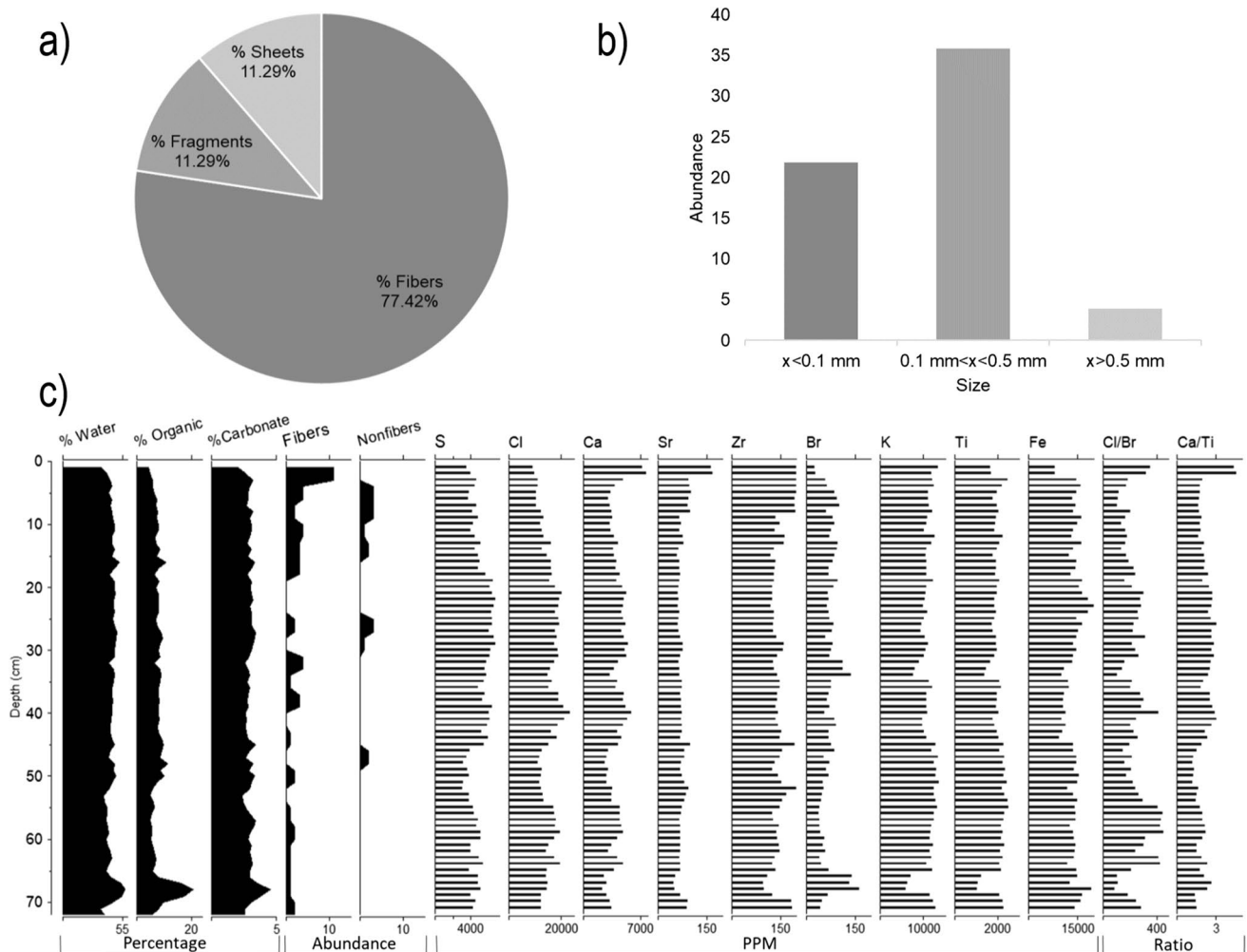
Fig. 5 (a) The percentage of each morphotype of microplastic found throughout core BC-C, including fibers, fragments, and sheets. No other morphotypes of microplastic were found in core BC-C. (b) The distribution of the three major size ranges of microplastic pieces in core BC-C. (c) LOI, microplastic morphotype abundance, and XRF data
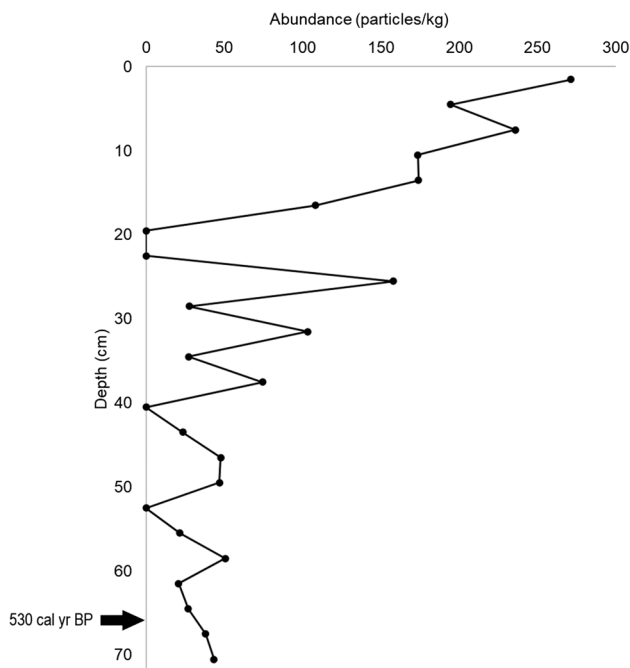
Core LLSWMA-4

Chronology

While dating was not completed on LLSWMA-4, ^{137}Cs and ^{14}C radiometric dating were completed on another core from Little Lake in a previous study providing relative dating information (Ryu 2020). The two cesium peaks in core LLSWMA-1 occurred at depths of 51 cm (indicating 1963 CE) and 54 cm (indicating 1954 CE), and a ^{14}C date of 682 cal yr BP was obtained from an organic rich bulk sediment sample at 92 cm depth (Schottler & Engstrom 2006; Ryu 2020). Assuming that cores LLSWMA-1 and LLSWMA-4 have similar sedimentation rates, which is reasonable, the 1950 CE sediment horizon in LLSWMA-4 is expected to occur around 54 cm depth, and the deepest sediment tested (90 cm) of LLSWMA-4 is expected to be approximately 682 cal yr BP.

Microplastic stratigraphy

The total abundance of microplastic found in core LLSWMA-4 was 231 pieces. The microplastic morphotypes present in this core were fibers and fragments, with no other microplastic morphotypes found in this core (unlike core BC-C, no sheets were found). Fibers were by far the most abundant microplastic morphotype in Core LLSWMA-4, with 226 (97.84%) being fibers and the remaining 5 (2.16%) being fragments (Fig. 7a). However, of the 10 different color groups of microplastics found in this core, only 6 of the 10 were fibers (black, blue, red, clear, brown, and purple), and 4 were fragments (black, white, red, and translucent red).

Fig. 6 Downcore abundance of microplastics per kilogram of sediment from core BC-C

Similar to core BC-C, the size range of microplastics within core LLSWMA-4 was dominated by mid-range, 0.1–0.5 mm microplastics (169 pieces; 73.2%; Fig. 7b). The other two sizes were relatively uncommon in comparison, with the small range (< 0.1 mm) having 39 (16.9%) and the large range (> 0.5 mm) having only 23 (9.9%). The average size of all microplastic pieces downcore was 0.25 mm.

A prominent peak in microplastic abundance occurs in the sample between 15 and 18 cm depth. This microplastic maximum is embedded in a 10 cm-thick layer of clayey sediments containing two layers of organic detritus rich in calcareous materials, as reflected by dramatic fluctuations in the percentages of water, organics, and carbonates in the 11–21 cm segment of the core (Fig. 7c). A similar clay layer, suggestive of an event deposit, was discovered in a core (core LLSWMA-1) taken in a marsh from another part of Little Lake and has been attributed to intense hurricanes Katrina and Rita of 2005 based on the ^{137}Cs dating results (Ryu 2020). The hurricanes made landfall about four weeks apart, and brought high storm surge, heavy rainfall, and extensive flooding to coastal Louisiana (Knabb et al. 2005, 2006). It is likely that the increased discharge from the Mississippi and local rivers and bayous, as well as polluted floodwaters draining from the extensively flooded urban areas of New Orleans to the north, carried an increased load of microplastics that were deposited in the Little Lake area. Thus, the sharp increase in microplastic concentration associated with the Katrina/Rita storm deposit supports the idea that

storms and flood events are major vectors for introducing microplastics into estuarine and coastal environments.

Microplastics were found in every sample throughout core LLSWMA-4 (Fig. 8). The highest concentration was found at the top of the core (4,366 pieces/kg), with a dramatic decrease immediately following. A smaller peak in concentration (1,898 pieces/kg) was found in the sample taken from 15–18 cm which, as discussed earlier, was likely deposited by floodwaters from hurricanes Katrina and Rita. While a general trend of lower concentration was found downcore (an average of around 142 pieces/kg from 25 cm depth through the end of the core), the average concentration throughout the core was about 502 pieces/kg.

It is remarkable that an estimated average of ~ 93 pieces/kg was still present below the 1950 CE layer around 54 cm. The presence of microplastic in sediments older than 1950 CE, even at much lower concentrations than in the samples above this horizon (an average concentration of ~ 738 pieces/kg was found above this layer), suggests that there was some degree of vertical mixing or reworking in the sedimentary stratigraphy, likely attributable to bioturbation.

FTIR spectroscopy

While no microplastic pieces from core BC-C were sufficiently large enough to test, FTIR spectroscopy was completed on two representative microplastic samples within core LLSWMA-4 to determine the polymer type. The red fiber that was tested was confirmed to be composed of nylon 6, a common plastic whose applications include textile production and, more likely for this region, fishing nets (Vagholkar 2016). The other piece was a white fragment which was confirmed to be vinyl chloride/polyvinyl chloride (PVC), a highly produced (36 million tons in 2008) plastic with a wide variety of uses including piping, cable insulation, and packaging (Lithner et al. 2012; Nakem et al. 2016). As this is a common material used for industrial purposes, it is not surprising to find it deposited in the sediment in this highly trafficked area.

Discussion

While the two study sites are both situated in an estuarine and coastal setting and are connected via a broad waterway, they differ significantly in the assemblage and abundance of microplastics downcore. Core BC-C had a greater overall variety of microplastic morphotypes (e.g., two types of sheets were found in BC-C but none were found in LLSWMA-4), but the total quantity and concentration per kg of sediment were vastly lower than in LLSWMA-4 (an average of 502 pieces/kg in LLSWMA-4 versus an average of 78
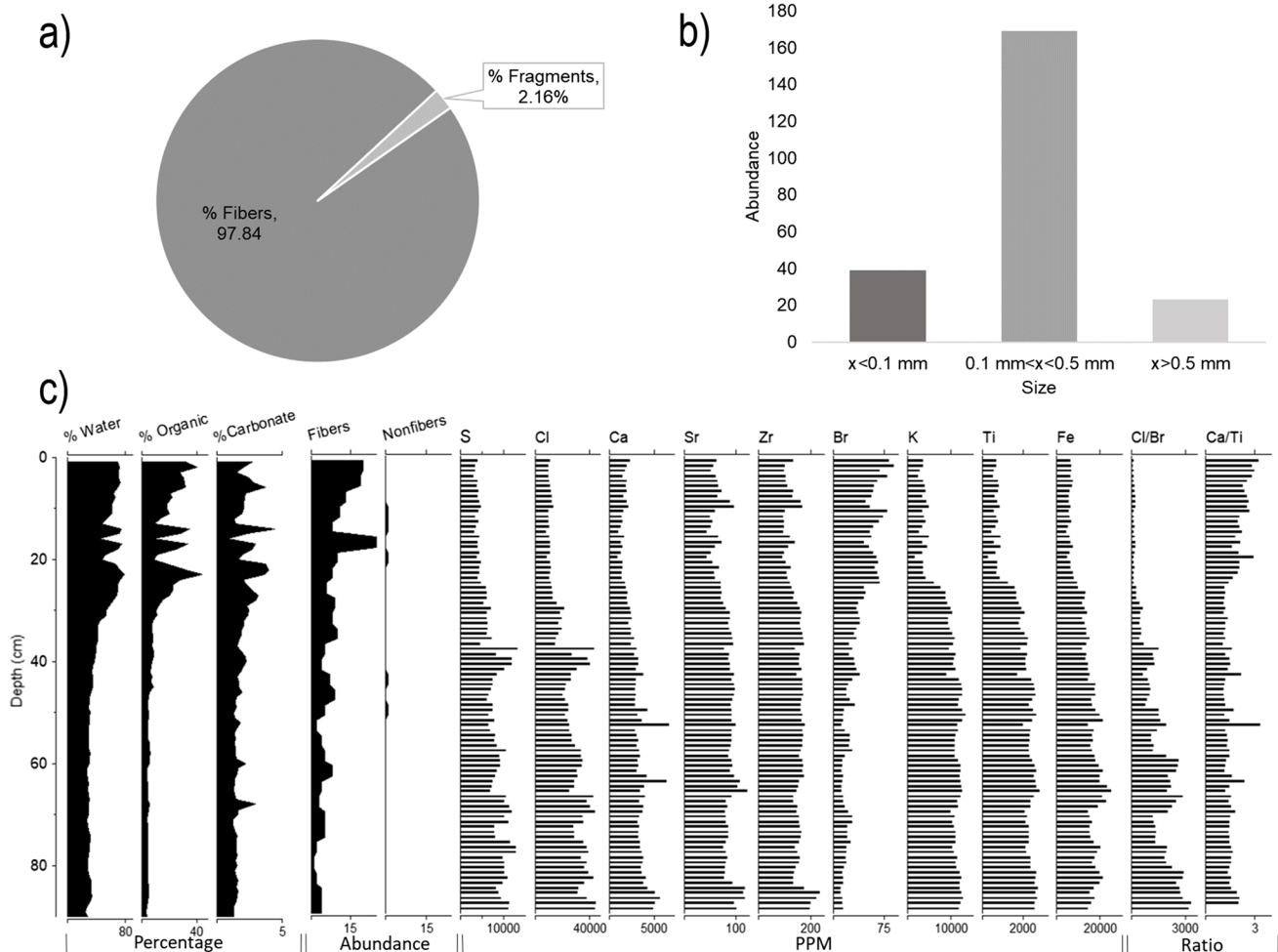
Fig. 7 (a) The percentage of each microplastic morphotype found in core LLSWMA-4, including fibers and fragments. No other morphotypes of microplastic were found in this core. (b) The distribution of the three major size ranges of microplastic pieces in core LLSWMA-4. (c) LOI, microplastic morphotype, and XRF data

pieces/kg in BC-C; the LLSWMA-4 average concentration was nearly 6.5 times higher; Fig. 9). Because Bay Champagne is adjacent to the industrial facilities of Port Fourchon, it is possible that it is exposed to a wide variety of plastics that are used in the shipping and petroleum industries that do business close to Bay Champagne.

Contrary to BC-C, the relatively homogenous microplastic makeup of core LLSWMA-4 may be because it is upstream of Port Fourchon and the surrounding industrial waterways, so is not as directly impacted by the facilities that are around Port Fourchon. However, the much greater abundance of microplastic is likely attributable to two external factors that Bay Champagne does not have: urban areas and the fishery. Because of the proximity to New Orleans, water from the metro area can flow into Little Lake through the Barataria Waterway (Tupitza & Glaspie 2020), transporting microplastic (e.g., from stormwater runoff or roadside littering) to the downstream Little Lake, increasing the amount of

microplastic in the sediment column. Additionally, the most common industry around Little Lake is the fishery, so direct introduction of microplastic into the environment from nets and fishing lines will likely also increase the abundance of microplastic within the lake (Hughes et al. 2002).

The red fiber from core LLSWMA-4 was confirmed by FTIR spectroscopy to be nylon 6, a common compound that is used in fishing nets (Vagholkar 2016). Nets often slough material when exposed to mechanical abrasion, including the friction between the net and the estuary bottom when trawling for benthic organisms (shrimp, crabs, etc.) (Xue et al. 2020). Red fibers exhibiting identical morphological characteristics (inferred to be nylon 6) were found in both cores, but core LLSWMA-4 had a much higher abundance downcore than BC-C (23 versus 3, respectively). This is likely because the region where core LLSWMA-4 was taken (Little Lake) is a much higher trafficked area for the commercial shrimp and crab fishing industry than the relatively
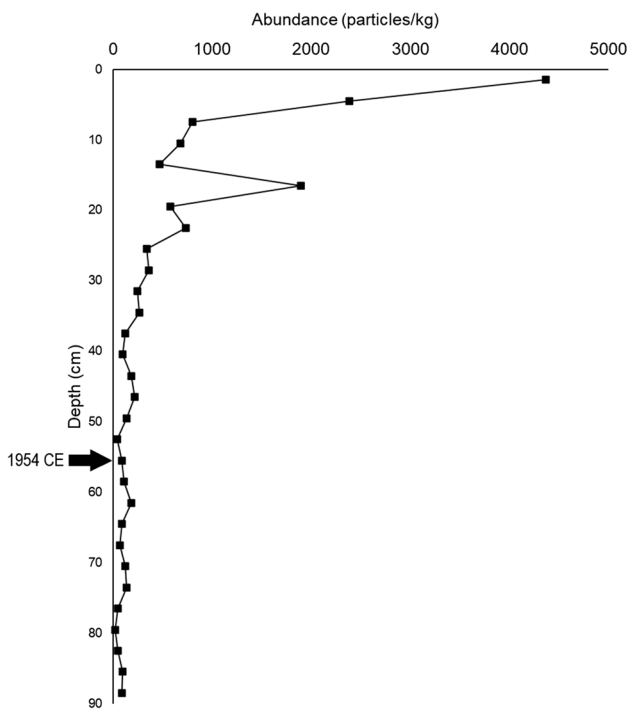
Fig. 8 Downcore abundance of microplastics per kilogram of sediment in core LLSWMA-4
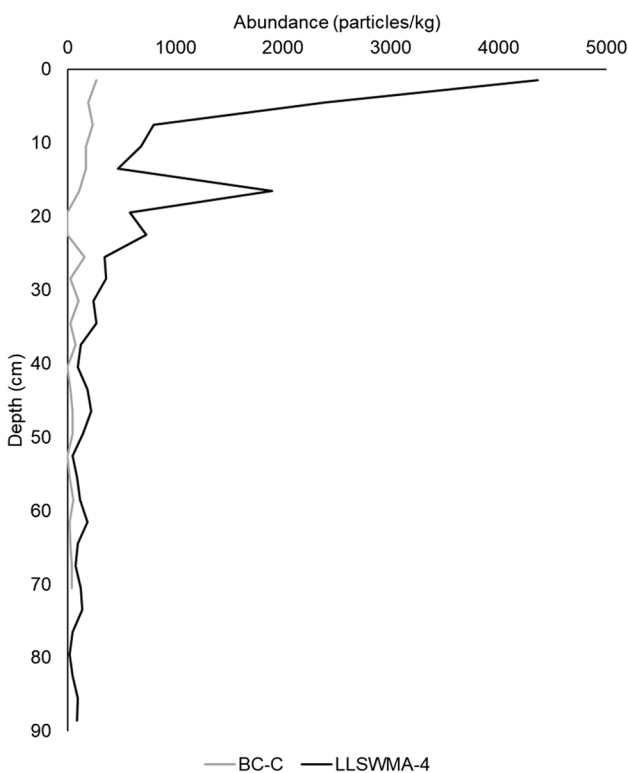
Fig. 9 Microplastics abundance downcore for cores BC-C and LLSWMA-4. LLSWMA-4 had a much higher abundance per kg than BC-C

small and isolated Bay Champagne (Curole 1991). The deposition of these fibers and their presence downcore may suggest that the commercial fishing industry is one of the leading sources of microplastic contamination in southern Louisiana estuaries.

Both cores had microplastics through to the bottom of the core, even beyond the presumable 1950 sediment horizon. Plastics should not have been deposited in sediment below these depths, or at least have been deposited in extremely low numbers due to their lack of production and widespread use before 1950. Therefore, alternate mechanisms must be responsible for this phenomenon. Bioturbation and/or high energy oceanographic events (both of which are common in south Louisiana estuaries) may be responsible for reworking and vertical transport within the sediment column, providing, according to Xue et al. (2020), a vector for "fresh microplastics preservation in old sediment" (Turra et al. 2014; Xue et al. 2020). High energy events (e.g., hurricanes and floods) are common in southern Louisiana, with four major hurricanes passing within 60 nautical miles of both sites at category 4 strength (wind speeds in excess of 131 mph) since 1950 (Betsy in 1965, Carmen in 1974, Andrew in 1992, and Katrina in 2005) (NOAA Office for Coastal Management 2021). These hurricanes and related flood events may be one reason that microplastic can be found in relatively high concentrations in certain layers deeper within the sediment column (i.e., 15–18 cm depth in core LLSWMA-4). However, the most likely explanation for small amounts of microplastic in downcore samples is bioturbation, as bioturbation can create local vertical mixing within the sedimentary column without destroying the stratigraphic integrity of the sediment stratigraphy (Xue et al. 2020). Intensive lithological, geochemical, and palynological studies of the sediment cores from Bay Champagne and Little Lake, coupled with results from radiometric dating, have shown that the overall sedimentary structure and stratigraphy at both sites are well preserved (Liu et al. 2011; Dietz 2019; Ryu 2020).

Physical movement of microplastics by benthic organisms up to 20 cm downward in the sediment column has been confirmed to occur during ingestion and defecation (Gebhardt & Forster 2018). While organisms may move microplastic from the surface deeper in the sediment column, it is not a uniform mixing. Two similar previous studies found a clear and significant decrease in microplastic abundance following an increase in depth, with microplastic particle concentration remaining high in the top 4 cm in a low bioturbation setting (Gebhardt & Forster 2018; Xue et al. 2020). One of these studies also found microplastics at the base of their core (60 cm depth) in sediment that was dated to 1897 (well before plastics were widely used) and transportation by marine worms was the likely cause (Xue et al. 2020). South Louisiana estuaries contain abundant burrowing invertebrates (e.g., crustaceans, polychaetes, and mollusks) that

modify local sediments, allowing for mixing of new microplastics into older sediment without violating the stratigraphic integrity of the whole sediment column (O'Connell et al. 2005; Xue et al. 2020). While major oceanographic events like hurricanes may be the cause of increased abundance of microplastics within individual layers, bioturbation is the likely driver for transporting microplastics downcore after deposition.

This general increase in concentration of microplastic from the bottom to the top of each core is commensurate with the global annual production of plastic (Fig. 1 and 9). Low production amounts in the 1950s-1970s leading to higher production in the decades since is proportional to the rates of microplastic deposition seen in the core samples. While the recent sediments in both cores were not directly dated by short-lived radioisotopes such as ^{137}Cs and ^{210}Pb, the trend of increasing microplastic pollution nearer to the sediment surface is consistent with increased global production and use in recent decades. Thus, a positive relationship between global plastic production and microplastic pollution abundance is certainly present.

Previous studies have suggested that downcore sediments (deeper than 5.5 cm) may contain up to five times as many microplastics by absolute abundance as are present in surface sediments (Turra et al. 2014; Xue et al. 2020). The two cores in this study follow this trend, as total microplastic abundance in downcore sediments (integrating several decades of sedimentation) are multitudes higher than those in surface sediments. In the top two samples (considered surface sediments; 0–6 cm depth) in Core BC-C, 17 microplastics were present. Downcore (6–72 cm), 45 microplastics were present, 2.65 times more than in the surface sediments. In core LLSWMA-4, the surface sediments contained 39 microplastics, while the downcore total (6–90 cm) was 192 pieces, 4.92 times more. Individually, only one downcore sample (6–9 cm in core BC-C) had a higher concentration than surface sediments, and this was likely caused by a flood event as inferred from geochemical data (Dietz 2019). Similarly, the layer deposited by Hurricanes Katrina and Rita in core LLSWMA-4 (15–18 cm) had a much higher concentration of microplastic than surrounding layers, but unlike the possible flood layer in core BC-C, it was still less than the average concentration of the surface layers. The surface average concentration was 1.78 times the amount of the hurricane layer showing that recent rates of microplastic deposition outpace even those of previous hurricane events. However, the combined total abundance in the downcore samples of both cores greatly exceeded that of the surface sediment because the downcore sediment column integrates more than six decades (1950-2010s) of microplastic accumulation. These results provide further evidence of downcore sediments acting as a major sediment sink for microplastics (Turra et al. 2014; Xue et al. 2020).

While any amount of microplastics in the environment is detrimental to the ecology of an area, if the microplastics are sequestered in deep sediment that is not resuspended or disturbed by bioturbation, high energy oceanographic events, or anthropogenic causes, then those microplastics will not be available for accidental uptake into the food web. Therefore, if plastics pollution can be reduced or even negated, those microplastics that are already present in the coastal environment may eventually be entirely sequestered, leading to a future with few negative impacts of microplastic on the ecology of coastal systems.

Conclusions

Microplastics are a common pollutant found in ocean waters and surface sediment worldwide, but to date few studies have investigated their vertical distribution within the sediment column (Cózar et al. 2014; Turra et al. 2014; Xue et al. 2020). The southern Louisiana coastline is a highly trafficked area that provides multiple possibilities for sources of plastic pollution, including the petroleum, shipping, and commercial fishing industries that utilize this productive region (Adams et al. 2004; Cieslak 2005; Jessen 2006; Browne 2015). This study examined downcore microplastic abundance in two cores from two sites around the Port Fourchon/Barataria Basin region and resulted in several findings:

1) Industrial activities in and around Port Fourchon (including the petroleum and shipping industries) are the likely cause of the wide variety of microplastic morphotypes found in Bay Champagne. However, while Bay Champagne was much closer to Port Fourchon than Little Lake, the total abundance of microplastic was much lower.

2) Microplastic abundance was much higher in core LLSWMA-4 than in core BC-C even though it was upstream of the nearest industrial source, Port Fourchon. The high abundance of nylon 6 fibers (commonly used in fishing nets) present in core LLSWMA-4 suggests direct deposition of some of the microplastic in Little Lake from the commercial fishery (Curole 1991; Vagholkar 2016; Xue et al. 2020), while the high concentration found in sediment layers attributed to hurricanes Katrina and Rita suggest stormwater runoff from New Orleans is another significant source.

3) In both cores, microplastic concentrations (measured in number of particles per kilogram of sediment by weight) decreased significantly downcore, with the highest concentration occurring at the surface. However, downcore sediments still act as a major sink for microplastic, as the total combined abundance of microplastics below 6 cm, representing the cumulative amount sequestered

over several decades, is multitudes higher than in surface sediments (2.65 times higher in BC-C and 4.92 times higher in LLSWMA-4). This microplastic sequestration may eventually benefit the ecology of coastal areas by preventing the accidental introduction of microplastics into the food web, as long as the microplastics remain buried in the sediment and are not constantly being reworked into the water column by high-energy events, bioturbation, or human activities.

4) Sediment resuspension and mixing by hurricanes, bioturbation, and trawling are each possible causes of microplastic being present below the presumptive 1950 sediment horizon. However, the likely explanation in this study is bioturbation. The stratigraphic integrity of the cores was confirmed through intensive lithological, geochemical, and palynological tests and microplastic concentration in individual downcore samples was relatively low compared to layers closer to the surface. This suggests that these mixing events are likely relatively infrequent and their effects are not ubiquitous, indicating microplastic movement via bioturbation.

While this study focused on coastal Louisiana estuaries, future microplastic studies can continue to provide a better understanding of the transport and deposition of microplastics in and around the world's oceans and coasts, their possible uses for determining the impacts of high energy events, and the negative impacts they have on the ecology of these sensitive areas. While sequestration within coastal and marine sediments may eventually mitigate some of the negative impact of microplastics, the persistent increase in production and improper disposal of plastics will continue to release microplastics in the environment at increasing rates, preventing any meaningful mitigation in the near future.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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