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First account of plastic pollution impacting freshwater fishes in the Amazon: Ingestion of plastic debris by piranhas and other serrasalmids with diverse feeding habits[☆]

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ABSTRACT

Reported here is the first evidence of plastic ingestion by freshwater fishes in the Amazon. Plastic bags, bottles, fishing gear, and other products are entering Amazonian water bodies and degrade into meso- and micro-plastic particles that may be ingested, either directly or indirectly via food chains, by fishes. Examination of stomach contents from 172 specimens of 16 serrasalmid species from lower Xingu River Basin revealed consumption of plastic particles by fishes in each of three trophic guilds (herbivores, omnivores, carnivores). Overall, about one quarter of specimens and 80% of species analyzed had ingested plastic particles ranging from 1 to 15 mm in length. Fourier transform infrared spectroscopy indicated 12 polymer types, including 27% identified as polyethylene, 13% polyvinyl chloride, 13% polyamide, 13% polypropylene, 7% poly(methyl methacrylate), 7% rayon, 7% polyethylene terephtalate, and 13% a blend of polyamide and polyethylene terephtalate. Dimensions of ingested plastic particles varied among trophic guilds, even though the frequency and mass of ingested particles were not significantly different among fishes with different feeding habits.

1. Introduction

Plastic debris has been reported to be the most pervasive form of anthropogenic litter in oceans (Jambeck et al., 2015) and freshwater systems worldwide (Vincent et al., 2017). Most plastic waste entering the ocean travels from land to sea by streams and rivers (Eerkes-Medrano et al., 2015; Zhang et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017). Plastic bottles, bags and fishing nets eventually fragment into smaller particles (microplastics < 5 mm, and mesoplastics 5.1–25 mm) that persist for long periods in the environment (Fossi et al., 2017), and plastic fragments have been found even in remote areas with little or no human population (Lusher et al., 2015a; Cincinelli et al., 2017; Lavers and Bond, 2017).

Plastic debris has become ubiquitous with potential impacts to fish and wildlife when ingested, either directly or indirectly when contained within the bodies of food items (Fossi et al., 2017). Ingestion of plastic debris can cause internal injuries and blockage of the gastrointestinal tract, which can lead to starvation (Possatto et al., 2011; Rummel et al., 2016; Tanaka and Takada, 2016; Courtene-Jones et al., 2017). Studies have documented plastic ingestion by invertebrates and birds (Lourenço et al., 2017), mammals (Lusher et al., 2015b), turtles (Matiddi et al., 2017), zooplankton (Setälä et al., 2014), fishes and other taxa (Santillo et al., 2017). In addition to interfering with feeding mechanics or blocking the gastrointestinal tract, plastic debris poses chemical toxicological risks via food chain transfer and bioaccumulation, which can pose a danger to humans who consume fish (Farrell and Nelson, 2013; Wright et al., 2013).

Here we report plastic ingestion by fishes in the Xingu River, a

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major tributary of the lower Amazon River. We analyzed stomach contents of fishes in the family Serrasalmidae, a group that includes carnivorous piranhas as well as herbivorous and omnivorous species. The broad range of feeding habits displayed by this group is associated with diverse functional traits; for example, flat incisiform teeth are efficient for cutting leaves (e.g., *Tometes* spp.) or flesh (e.g., *Serrasalmus* spp.) and molariform teeth are effective for crushing seeds (e.g., *Myloplus* spp.) (Nico et al., 2017). Some serrasalmids, such as pacus, specialize on leaves, fruits and seeds, whereas others, such as piranhas, consume mostly fish. Serrasalmid specimens were collected from the lower Xingu Basin, and their stomach contents were examined to determine: (1) frequency of plastic particles ingested, (2) polymer composition of ingested plastic, (3) relationship between plastic ingestion and trophic guild, and (4) potential pathways for transfer of plastic within the food web.

2. Materials and methods

2.1. Study area and examined specimens

The Xingu River, the largest clear-water tributary of the Lower Amazon River (Goulding et al., 2003), was selected for study because of its high diversity of serrasalmid fishes with distinct feeding habits. The study area (Fig. S1) was a river reach of about 310 km from the Xingu River mouth (2°35′30″S 51°57′14″W) upstream to a location in the Iriri River 15 km above its confluence with the Xingu River (3°51′10″S 52°43′40″W), plus a stretch of the Bacajá River from its confluence with the Xingu (3°30′19″S 51°42′47″W) to a location 40 km upstream (3°45′26″S 51°34′57″W). The region has been impacted by hydroelectric dams and pollution, including plastic waste that enters into streams and rivers (MMA/IBAM, 2005). Fishes were surveyed between July 2012 and November 2014 at several sites in the study reaches, and specimens selected for study were preserved in 70% EtOH and later deposited in the ichthyological collection of the Grupo de Ecologia Aquática (GEA) at Federal University of Pará (UFPA).

2.2. Contamination control

All samples were processes in a laminar flow hood under contamination-controlled conditions. Before its use for preserving the specimen, ethanol was filtered (5-μm porosity). Filtered ethanol was used to wash glass Petri dishes and dissecting instruments before and after use. To check for potential contamination by airborne particles, five clean Petri dishes were placed on the lab bench at the beginning of each work session and examined under stereomicroscope at the end of the session. No attempts were made to identify clothing fibers or other kinds of tiny particles that were not easily distinguishable from natural foods, such as plant fibers. All of the items recovered from control Petri dishes were smaller than the plastic particles we recorded from stomach contents.

2.3. Stomach contents analyses

Fish specimens were measured for standard length (SL) using digital calipers (to nearest 0.01 mm) and weighed on a digital scale (to nearest 0.01 g) prior to dissection and removal of the stomach. Empty stomachs were excluded from the dietary analysis. Stomachs were cut longitudinally using a clean scalpel, and the contents washed to a Petri dish using the filtered ethanol. Stomach contents were examined under a stereomicroscope, and items were categorized as either natural food or plastic debris and then weighed to the nearest 0.0001 g (Shimadzu Analytical Balance, model AUY220). The each plastic item was measured to the nearest 0.001 mm (Zeiss SteREO Discovery.V12 using Zen Software; blue edition, v2.0), sorted as microplastic (<5 mm) or mesoplastic (5.1–25 mm) (Fossi et al., 2017), and further classified according to shape and color.

2.4. Dietary composition

One hundred and seventy-two specimens, representing 16 species of the family Serrasalmidae from the lower Xingu River Basin, were examined (Table 1). SL ranged from 42.5 to 271.7 mm, and body weight (W) ranged from 2.0 to 844.2 g. Five species accounted for about 70% of the total sample: *Tometes kranponhah* (36.6%), *Ossubtus xinguense* (11.0%), *Myloplus rubripinnis* (8.7%), *Pristobrycon* cf. *scapularis* (8.1%), and *Metynnis guaporensis* (6.4%). Two species, *Metynnis luna* and *Myloplus rhomboidalis*, were represented by a single specimen (0.6% of the sample).

Food items recovered from fish stomachs were identified according to the following categories: aquatic macrophytes (including fragments of leaves and stems of aquatic macrophytes, mainly Podostemaceae), birds (fragments of toes and feathers), fishes (pieces of muscle, scales and fins, mostly Characiformes), macroinvertebrates (larvae of insects, mainly Chironomidae and Simuliidae), mollusks (shells and flesh of aquatic gastropods), periphyton (algae and associated particulate organic matter), plants (leaves and stems of terrestrial plants), seeds (seeds of terrestrial plants), and zooplankton (mainly the genus *Daphnia*).

2.5. Polymer analyses

We applied Fourier Transform Infrared (FTIR) spectroscopy since this is the most reliable method to identify the composition of plastic debris, using either single-element or Focal Plane Array (FPA) detectors (Srinivasa Reddy et al., 2006; Mecozzi et al., 2016; Cincinelli et al., 2017; Primpke et al., 2017; Simon et al., 2018; Pegado et al., 2018). FTIR spectra were collected in Attenuated Total Reflectance (ATR) mode, using a single-element MCT detector, which was deemed as the optimal set up, given the type and morphology of plastic items recovered from fish stomachs. ATR-FTIR analysis was performed using a Thermo Nicolet Nexus 870 FTIR spectrometer. The spectra were collected using a Golden Gate diamond cell, with a spectral resolution of 8 cm^{-1}, acquiring 128 scans for each spectrum in the 4000-400 cm^{-1} spectral range.

2.6. Data analysis

Interspecific variation in diet composition was assessed using shade-plot (*heat map*) (Clarke et al., 2014), whereby the relative importance of food categories is based on frequency of biomass ingested. Plastic items were excluded from this dietary analysis. Fish guilds were assigned using group-averaged cluster analysis based on the Bray–Curtis similarity of diet matrix.

To test for statistically significant differences in plastic intake among species and guilds, we analyzed frequency of occurrence, percentage of the plastic weight, and plastic length using a univariate permutational analysis of variance (PERMANOVA) based on Euclidean distance matrices with 9999 permutations, and data distributions examined in violin plots.

Trophic linkages among fish guilds and the evaluation of plastic intake by guilds were assessed from frequency of occurrence of the ingested items in a bipartite network (Dormann et al., 2008) in R (R Development Core Team, 2017). To build this intake network, we combined the items consumed by three trophic guilds to create a G × I matrix, where I is the frequency of occurrence items, and G is the specimens from guilds.

Table 1
Ranges and mean values of the fish length and weight for 16 serrasalmid species collected from the lower Xingu Basin. N, number of stomachs analyzed; SD, standard deviation.

Species	N	Standard length (mm)		Weight (g)	
		Range	Mean ± SD	Range	Mean ± SD
Acnodon normani	4	94.8–144.8	116.7 ± 21.9	11.3–28.8	21.1 ± 7.4
Metynnis guaporensis	11	75.2–90.8	85.3 ± 4.0	23.7–33.4	27.8 ± 3.5
Metynnis luna	1	45.7	–	4.7	–
Myloplus asterias	4	132.9–140.3	137.4 ± 4.0	140.3–192.7	161.0 ± 22.4
Myloplus rhomboidalis	1	63.1	–	9.9	–
Myloplus rubripinnis	15	53.6–257.4	100.3 ± 68.1	6.7–844.2	129.8 ± 239.6
Myloplus schomburgkii	6	42.5–57.4	50.8 ± 5.6	3.9–8.1	6.0 ± 1.5
Ossubtus xinguense	19	50.3–203	123.9 ± 59.1	3.3–363	157.7 ± 140.4
Pristobrycon cf. *scapularis*	14	87.2–152.6	108.8 ± 21.1	30.6–178.2	68.0 ± 48.4
Pristobrycon eigenmanni	6	49.4–154.7	119.1 ± 38.5	5.5–200.2	106.1 ± 72.0
Pygocentrus nattereri	4	130.3–150.1	140.0 ± 8.5	79.5–97.8	88.0 ± 7.5
Serrasalmus cf. *altispinis*	3	99.5–164.4	141.5 ± 36.4	28.8–155.4	78.0 ± 67.8
Serrasalmus manueli	7	80.3–175.3	112.6 ± 35.7	11.2–197.2	62.3 ± 70.3
Serrasalmus rhombeus	9	43.0–132.3	76.1 ± 27.5	2.0–79.1	20.2 ± 25.1
Tometes ancylorhynchus	5	48.4–74.9	54.9 ± 11.2	4.2–16.9	7.4 ± 5.3
Tometes kranponhah	63	45.8–271.6	79.1 ± 30.5	4.2–776.2	33.2 ± 96.6

3. Results

3.1. *Fish diets*

Three trophic guilds were indicated in the dendrogram derived from cluster analysis constructed from the weight of food categories consumed by the 16 species (Fig. 1). A carnivore guild was comprised of six piranhas; an herbivore guild contained five species, and an omnivore guild had five species (Table 2). Although the shade plot revealed that each guild consumed at least some amount of every food category, it clearly indicated that carnivores fed heavily on fish, and consumed minor proportions of terrestrial plants (plant material was ingested mainly by *P.* cf. *scapularis*, *S. manueli*, *S.* cf. *altispinis*). The herbivore guild fed mostly on terrestrial plant material. The omnivore guild consumed significant portions of terrestrial plants, aquatic macrophytes, and aquatic macroinvertebrates (Table 2, Table S1).

3.2. *Plastic ingestion by serrasalmids*

Overall, 96 plastic items were recovered from stomachs of 46 specimens (26.7%) among the 172 specimens examined. Thirteen out of 16 species (81.3%) had consumed plastic, with only *Metynnis luna* (N = 1) and *Myloplus asterias* (N = 4) both belonging to the herbivore guild, and *Serrasalmus* cf. *altispinis* (N = 3) from the carnivore guild, lacking evidence of plastic ingestion. However, the absence of plastic debris in these three species may be attributed to the small sample size. The frequency of occurrence of ingested plastic items by species ranged from 13.3% for *Myloplus rubripinnis* (2 of 15 specimens) to 100% for *Myloplus rhomboidalis* (the single specimen that was examined).

Excluding the three species lacking evidence of plastic ingestion, herbivores had lowest percent frequency of occurrence of plastic in their stomachs (ranging from 13.3% for *Myloplus rubripinnis* to 27.3% for *Metynnis guaporensis*) (Table 3). Omnivores had the highest percent frequency of occurrence, ranging from 25.0% for *Acnodon normani* to 100% for *Myloplus rhomboidalis* (Table 3). Frequency of occurrence of plastic in carnivore stomachs ranged from 14.3% for *Semasalmus manueli* to 75.0% for *Pygocentrus nattereri* (Table 3). Despite these differences, frequency of occurrence of plastic in stomachs was not significantly different among guilds based on PERMANOVA (pseudo-$F = 1.865$, $p = 0.15$, Fig. 2A).

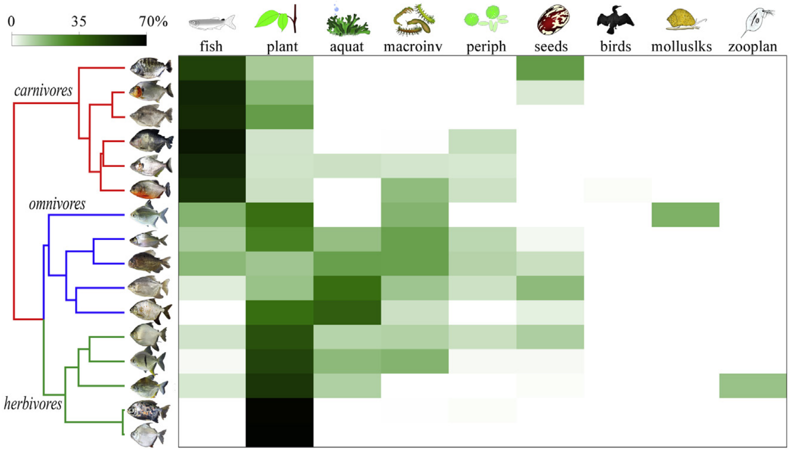

Fig. 1. Cluster and *shade plot* showing diet similarity among 16 serrasalmid species (fish figures from top to bottom): *Pristobrycon* cf. *scapularis*, *Serrasalmus manueli*, *Serrasalmus* cf. *altispinis*, *Serrasalmus rhombeus*, *Pristobrycon eigenmanni*, and *Pygocentrus nattereri* (▬ depicting the carnivore guild); *Myloplus rhomboidalis*, *Acnodon normani*, *Ossubtus xinguense*, *Tometes kranponhah*, and *Tometes ancylorhynchus* (▬ depicting the omnivore guild); *Myloplus rubripinnis*, *Myloplus schomburgkii*, *Metynnis* cf. *guaporensis*, *Myloplus asterias*, and *Metynnis luna* (▬ depicting the herbivore guild). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Number of specimens (N) examined by species of each guild, and average weight of food items found in stomachs of serrasalmid fishes from Xingu River Basin. AQM: aquatic macrophytes; BIR: birds; FIS: fish; INV: macroinvertebrates; MOL: mollusks; PER: periphyton; PLA: phytoplankton; SEE: seeds; and ZOO: zooplankton.

Guild/Species	N	AQM	BIR	FIS	INV	MOL	PER	PLA	SEE	ZOO
Carnivores										
Pristobrycon cf. *scapularis*	14	0.005	–	1.465	–	–	–	0.395	0.804	–
Pristobrycon eigenmanni	6	0.135	–	0.236	0.056	–	0.100	0.031	–	–
Pygocentrus nattereri	4	–	–	1.354	0.998	–	0.399	0.408	–	–
Serrasalmus cf. *altispinis*	3	–	–	1.094	–	–	–	0.379	–	–
Serrasalmus manueli	7	–	0.002	1.145	–	–	–	0.344	0.377	–
Serrasalmus rhombeus	9	–	–	0.584	0.012	–	0.494	0.376	0.007	–
Herbivores										
Metynnis guaporensis	11	0.433	–	0.049	–	–	–	0.229	0.023	0.189
Metynnis luna	1	–	–	–	–	–	–	0.369	–	–
Myloplus asterias	4	0.001	–	–	0.004	–	0.005	0.274	–	–
Myloplus rubripinnis	15	0.528	–	0.940	0.303	–	0.379	1.241	0.518	–
Myloplus schomburgkii	6	0.373	–	0.012	0.205	–	0.023	0.212	0.009	–
Omnivores										
Acnodon normani	4	0.221	–	0.173	0.256	–	0.396	0.367	0.067	–
Myloplus rhomboidalis	1	–	–	0.430	0.430	0.453	–	0.919	–	–
Ossubtus xinguense	19	0.169	–	0.290	0.214	–	0.272	0.128	0.097	–
Tometes ancylorhynchus	5	0.229	–	0.003	0.082	–	–	0.197	0.083	–
Tometes kranponhah	63	0.420	–	0.120	0.158	–	0.252	0.259	0.250	–

Table 3
Frequency of occurrence of plastics (FOp%) per species, plastic weight as a percentage of total ingested food weight (PpW%), number of plastic particles (Np), microplastics (Nmic), mesoplastics (Nmes), and the ranges of plastic weight (W), microplastic particle length (Lmic), and mesoplastic particle length (Lmes), (Average ± Standard deviation) found in stomach contents of serrasalmid fishes from Xingu River Basin.

Guild/Species	FOp%	PpW%	Np	Plastic W g	Nmic	Lmic mm	Nmes	Lmes mm
Carnivores								
Pristobrycon cf. *scapularis*	42.9	14.7–34.5	8	0.001–1.5 (0.5 ± 0.4)	3	1.4–4.6 (2.6 ± 1.8)	5	5.9–14.9 (10.3 ± 4.1)
Pristobrycon eingenmanni	33.3	1.7–32.2	2	0.002–0.1 (0.1)	–	–	2	5.5–15.0 (10.3 ± 6.7)
Pygocentrus nattereri	75.0	14.5–24.4	3	0.4–0.4 (0.4 ± 0.01)	–	–	3	10.0–11.4 (10.6 ± 0.7)
Semasalmus manueli	14.3	19.5	1	0.4	–	–	1	5.5
Serrasalmus cf. *altispinis*	–	–	0	–	–	–	–	–
Serrasalmus rhombeus	22.2	0.03–47.2	3	0.0002–0.4 (0.1 ± 0.2)	–	–	3	8.3–10.6 (9.1 ± 1.3)
Herbivores								
Metynnis guaporensis	27.3	4.5–62.1	3	0.02–0.08 (0.06 ± 0.03)	–	–	3	7.3–11.5 (8.7 ± 2.4)
Metynnis luna	–	–	0	–	–	–	–	–
Myloplus asterias	–	–	0	–	–	–	–	–
Myloplus rubripinnis	13.3	11.5–16.3	5	0.03–0.4 (0.3 ± 0.2)	2	2.0–4.9 (3.5 ± 2)	3	7.0–13.7 (10.3 ± 3.3)
Myloplus schomburgkii	16.7	48.4	2	0.04–0.08 (0.06)	1	3.3	1	11.4
Omnivores								
Acnodon normani	25.0	12.6	1	0.06	–	–	1	8.8
Myloplus rhomboidalis	100	27.8	2	0.4–0.4 (0.4)	–	–	2	10.5–10.9 (10.7 ± 0.2)
Ossubtus xinguense	52.6	0.6–77.0	42	0.001–0.3 (0.06 ± 0.06)	11	1.7–4.3 (2.7 ± 0.9)	31	5.0–11.4 (7.3 ± 1.6)
Tometes ancylorhynchus	40.0	25.9–41.6	3	0.08–0.5 (0.1 ± 0.2)	–	–	3	6.0–11.3 (8.8 ± 2.7)
Tometes kranponhah	19.0	0.01–48.3	21	0.0001–0.5 (0.2 ± 0.2)	9	1.0–4.9 (2.5 ± 1.3)	12	5.8–11.4 (8.7 ± 1.6)

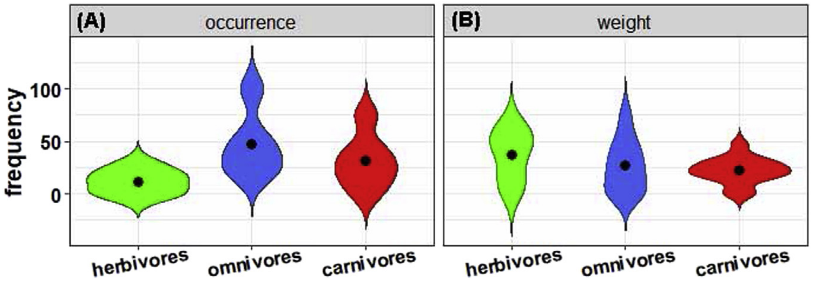

Fig. 2. Violin plots showing the (A) frequency of occurrence of plastic items recovered from serrasalmid fish stomachs from three trophic guilds, and (B) weight of the plastic items recovered from stomachs for guilds (based on percent weight of stomach contents that was plastic).

Plastic items recovered from fish stomachs ranged in weight from 0.0001 for *Tometes kranponhah* to 1.5 g for *Pristobrycon* cf. *scapularis* (Table 3). The plastic weight as a percentage of total ingested food weight ranged from 0.01% for *Tometes kranponhah* to 77% for *Ossubtus xinguense* (Table 3). The weight of ingested plastic did not differ significantly among the three guilds, and this was the case both when the test included all 172 available specimens (PERMANOVA, pseudo-$F = 1.042$, $p = 0.55$) and test included only specimens that had consumed plastic (PERMANOVA, pseudo-$F = 1.118$, $p = 0.49$, Fig. 2B). Excluding those species that had not consumed plastic, the proportion of the total stomach content weight that was plastic differed among guilds − ranging from 4.5% to 62.1% (average 36.7%) for herbivores, from 0.01% to 77.0% (average 26.8%) for omnivores, and from 0.03% to 47.2% (average 22.0%) for carnivores (Table 3).

Plastic debris found in serrasalmid stomachs ranged in length from 1.0 mm for *Tometes kranponhah* to 15 mm for *Pristobrycon eigenmanni* (Table 3). Serrasalmids ingested 29.2% microplastics (<5 mm) and 70.8% mesoplastics (5.1–25 mm). The violin plot in Fig. 3 depicts the plastic sizes ingested by each guild. The most common size interval of plastic particles ingested by herbivores was just over 10 mm, whereas the most common size class consumed by omnivores and carnivores was 7.5 mm (Fig. 3). The length of ingested plastic particles did not differ significantly among guilds (PERMANOVA, pseudo-$F = 2.315$, $p = 0.05$), and this also was the case when the analysis was limited to microplastics (pseudo-$F = 1.266$, $p = 0.41$). However, the length of mesoplastics differed significantly among guilds (pseudo-$F = 3.374$, $p < 0.01$). In paired comparisons, carnivores and herbivores did not differ significantly (pseudo-$F = -1.231$, $p = 0.22$), but differences were significant between omnivores and carnivores (pseudo-$F = 2.245$, $p < 0.05$) and omnivores and herbivores (pseudo-$F = 3.741$, $p < 0.01$).

Fig. 4 shows the bipartite network summarizing major trophic pathways and potential routes for plastic intake by serrasalmid guilds (Table S1). The highest intake of plastic particles was by omnivores (18.6%) and carnivores (16.0%), and lowest intake was by herbivores (10.2%).

3.3. Plastic characteristics

Twelve types of plastic were recovered from serrasalmid stomachs, and from 96 plastic items 15 items were randomly selected for polymer analysis, three of which consisted of joined layers of two different materials (see detailed polymer characterization under supplementary material). Four samples (27%) were identified as polyethylene (PE), two (13%) as polyvinyl chloride (PVC), two (13%) as polyamide, two (13%) as polypropylene (PP), two (13%) as a blend of polyamide and polyethylene terephtalate (PET), one (7%) as poly(methyl methacrylate) (PMMA), one (7%) as rayon (functionalized with acrylate), one (7%) as PET. Particles debris was classified into two categories: filaments, which are elongate strands; and fragments, which are particles of irregular shape. Filaments were slightly more common in stomach contents (53.1% of items) than fragments (46.9%). Black was the predominant color of plastics (28.1%), followed by shades of blue (19.8%), red (18.8%), white (14.6%), and translucent (8.3%) (Fig. 5A–F).

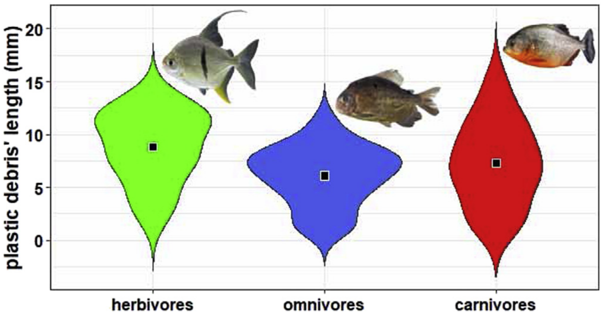

Fig. 3. Violin plot showing the length of plastic particles ingested by the serrasalmid fishes from Xingu River, Brazil.

4. Discussion

Our study appears to be the first to describe ingestion of plastic particles by Amazonian freshwater fishes. Plastics were confirmed in ~80% of species from three trophic guilds. According to a recent estimate, plastic waste exported by Amazon River to Atlantic Ocean could be as much as 60,000 tonnes year^{-1} (Lebreton et al., 2017). Equatorial regions with high temperatures and levels of UV radiation promote faster thermooxidative degradation and photodegradation of plastics (Maryudi et al., 2017). A recent study (Pegado et al., 2018) found that microplastics had been ingested by ~30% of fish species from trawl samples conducted in the Amazon estuary, and recent studies have reported the plastic ingestion by estuarine fishes from other regions of the Brazilian coast (e.g. Ramos et al., 2012; Costa and Barletta, 2015). A recent review (Vendel et al., 2017) found that comparatively few studies have reported evidence on plastic ingestion by freshwater fishes (e.g. Lechner et al., 2014; Phillips and Bonner, 2015; Silva-Cavalcanti et al., 2016; Pinheiro et al., 2017).

Plastic debris in rivers and lacustrine systems has not been well documented for most regions of the world (Hurley et al., 2018). However, plastic particles have been recorded in freshwater systems of North American (Miller et al., 2017), Europe (Gasperi et al., 2014) and Africa (Biginagwa et al., 2016). Plastic pollution tends to be greater near urban centers (Peters and Bratton, 2016; Hurley et al., 2018). Larger fish tend to ingest greater amounts of plastic particles, possibly because larger fishes tend to occupy higher trophic positions and would suffer most if there is bioaccumulation (Horton et al., 2018; Pegado et al., 2018).

Feeding behavior has been shown to play an important role in the ingestion of plastic debris by fishes (Jabeen et al., 2017). Variation in the sizes of particles ingested by serrasalmids of different trophic guilds likely is associated with behavioral differences. Omnivores feed heavily on aquatic macrophytes that probably intercept and retain tiny plastic particles drifting in currents. Herbivorous serrasalmids feed mostly on seeds, fruits, leaves and fragments from terrestrial plants. These herbivores might ingest larger plastic particles that are mistaken for food resources. Piranhas may ingest plastic when they consume prey that ingest and retain plastic particles. Interestingly, the three trophic guilds revealed relatively small differences in total numbers of ingested plastic particles. Vendel et al. (2017) similarly found few differences in amounts of plastic ingested by five trophic guilds. However, if we examine only small mesoplastics (49 items, ranging between 5.0 and 11.4 mm), then omnivorous serrasalmids had consumed more particles than carnivores (14 items, ranging between 7.0 and 13.7 mm) and herbivores (7 items, ranging between 5.5 and 15.0 mm).

The color of ingested plastic particles found in this study was predominantly black, but we also encountered blue, red, white, and translucent particles. Similarly to our results, Ory et al. (2018) identified that planktivorous juvenile fish preferentially ingested black plastic particles, which presumable have cues similar to those associated with their prey. Ory et al. (2017) found that the fish *Decapterus muroadsi* (Carangidae) in the southeastern Pacific Ocean ingested blue plastic particles that had optical properties similar to their copepod prey. Although it remains unclear why and how serrasalmid fishes ingest plastic particles, we do know that plastic pollution has become prevalent in the Amazon. Most of the plastics found in the present study commonly derive from degradation of plastic bags and bottles (e.g. polyamide, polyester, and polyethylene terephthalate), fishing gear (e.g. polyethylene), and other plastic products.

Some plastic debris apparently has an appearance similar to natural food items (Mauro et al., 2017) and, in certain cases, might

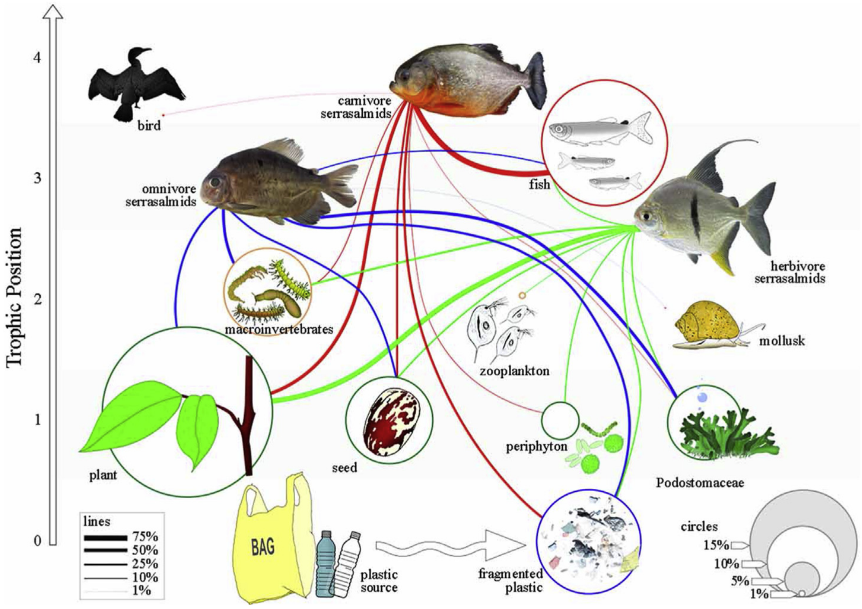

Fig. 4. Summary of trophic network showing pathways for intake of plastic debris by three guilds of serrasalmid fishes in the lower Xingu Basin.

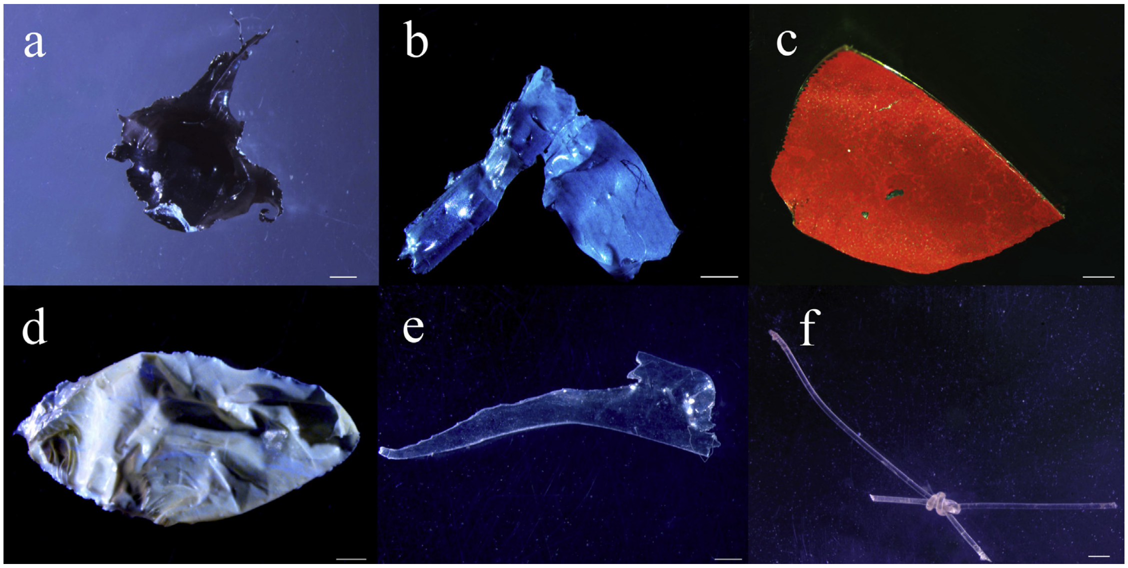

Fig. 5. Plastic debris from stomachs of serrasalmid fishes from the Xingu Basin. Examples of fragments (A–E) and filaments (F), and of the colors black (A), blue (B), red (C), white(D), and transparent (E–F). Scale bar = 1 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

even emit chemicals that function as olfactory attractants to organisms (Savoca et al., 2017). Some plastics are toxic; for example, exposure to polyethylene particles have been shown to be associated with histopathologic abnormalities (Karami et al., 2017a). Dynamics of plastics in food webs remain poorly documented but extend beyond factors associated with ingestion of plastic particles in the environment, because smaller particles can be transferred from the digestive tract to other parts of the body, such as muscle and organs tissues (Karami et al., 2017b). However, particles that are transported to, and retained within muscle and other tissues are considerably smaller (<1 mm) than the plastics particles recorded in the present study. In planktonic food webs, zooplankton ingest and retain microplastics, and whenever they are consumed by larval fish (Steer et al., 2017) and other zooplanktivores, this material is passed to higher trophic levels (Setälä et al., 2014).

5. Conclusions

This study appears to be the first to document ingestion of plastic by freshwater fishes in the Amazon. Contrary to our expectation, the three trophic guilds did not differ significantly in the frequency or magnitude of plastic ingestion. Although we examined stomach contents of species from just one freshwater fish family, our findings indicate that plastic pollution in the Amazon is already impacting aquatic fauna. Some of these plastic polymers likely originate from lost and discarded fishing gear (e.g. polyethylene in fishing line and nets), whereas other plastics undoubtedly derive from trash discarded throughout the watershed and washed into rivers with runoff. Polyamide, polyester, and polyethylene terephthalate are common materials used to make plastic bags, bottles, threads, and other products. Plastic pollution impacting the aquatic biota of the Amazon, also has large potential to harm the health and food security of humans who depend on fisheries and other ecosystem services.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2018.10.088.

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