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Original

Total mercury (T-Hg) in ichthyofauna with the highest consumption in San Marcos - Sucre, Colombia

Daniel Romero-Suárez[1]; Liseth Pérez-Flórez[2]; Adolfo Consuegra-Solorzano[2]; Jhon Vidal-Durango[3]; Jorge Buelvas-Soto[4]*; José Marrugo-Negrete[4].

[1]Universidad del Magdalena, Facultad de ciencias de la salud, Programa de medicina, Santa Marta, Colombia.
[2]Universidad de Sucre, Grupo de investigación Conservación del Recurso Hídrico y Alimentos (CRHIA), Sincelejo, Colombia
[3]Universidad de la Costa, Barranquilla, Colombia
[4]Universidad de Córdoba, Grupo de investigación Aguas, Química aplicada y Ambiental, Montería, Colombia
*Correspondence: jorge.buelvas.soto@gmail.com

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ABSTRACT

Objective. Hg was quantified in the dorsal muscle of the 11 species of fish most consumed in San Marcos, located in the region of La Mojana. **Materials and methods.** Dorsal muscle samples were taken from the fish species. T-Hg concentrations were quantified using cold vapor atomic absorption spectrophotometry (CVAAS). **Results.** The species with the highest T-Hg values were those with carnivorous eating habits: *Pseudoplatystoma magdaleniatum* (0.44 ± 0.09 µg/g), *Plagioscion surinamensis* (0.42 ± 0.14 µg/g) and *Hoplias malabaricus* (0.39 ± 0.11 µg/g). However, the maximum recommended amount of Hg in fish (0.5 µg/g) set by the European Union was not exceeded by any of the species studied. **Conclusions.** It is concluded that the commercial ichthyofauna of La Mojana is contaminated by Hg as a result of the mining activities that take place in the channels of the rivers that discharge in this region. The persistent consumption of fish from the evaluated areas by its inhabitants represents a high risk due to the high toxicity of Hg, which presents adverse effects on human health, even when it is consumed in low doses for prolonged periods of time.

Keywords: Environmental toxicology; fishing; food safety; heavy metals; mining; wetlands (*Sources: FAO*, *Environmental Thesaurus for Colombia*).

RESUMEN

Objetivo. Se cuantificó el Hg en músculo dorsal de las 11 especies de peces más consumidas en San Marcos, localizado en la región de la Mojana. **Materiales y métodos**. Se tomaron muestras del músculo dorsal de las especies ícticas, cuantificando las concentraciones de Hg-T mediante espectrofotometría de absorción atómica por vapor frío (CVAAS). **Resultados.** Las especies que presentaron los más altos valores de Hg-T fueron las de hábitos alimenticios carnívoros: *Pseudoplatystoma magdaleniatum* (0.44±0.09 µg/g), *Plagioscion surinamensis* (0.42±0.14 µg/g) y *Hoplias malabaricus* (0.39±0.11 µg/g). No obstante, la máxima cantidad recomendable de Hg en peces (0.5 µg/g) fijado por la Unión Europea, no fue superada por ninguna de las especies estudiadas. **Conclusiones.** Se concluye que

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la ictiofauna comercial de la Mojana está contaminada por Hg, resultado de las actividades mineras que se desarrollan en los cauces de los ríos que descargan en esta región. El consumo persistente de pescado proveniente de las zonas evaluadas por parte de sus pobladores representa un alto riesgo, debido a la alta toxicidad del Hg, el cual presenta efectos adversos en la salud humana aun cuando es consumido en dosis bajas durante periodos de tiempo prolongados.

Palabras clave: Humedales; metales pesados; minería; pesca; seguridad alimentaria; toxicología ambiental (*Fuentes: FAO, Tesauro ambiental para Colombia*).

INTRODUCTION

Mercury (Hg) is a neurotoxic metal that is increasingly present in the environment due to human activities (1). The inadequate management of Hg in gold mining areas has generated serious contamination processes in soils and aquatic ecosystems (2), which exponentially increases the risk of exposure to people through contaminated food products (3). Although there are many forms of exposure to Hg, direct inhalation of anthropogenic emissions and consumption of fish are the main routes of human exposure (4). Even when Hg concentrations are low in aquatic ecosystems, they can reach dangerously high levels in the biota of these environments, particularly in fish, due to the accumulation of this pollutant through the food web (5).

The activity that contributes the most to Hg contamination in Colombia is gold mining (6), being the north of Antioquia and south of Bolívar the areas with the greatest exploitation of this metal (7). A large part of this gold mining area is limited to La Mojana, an extensive region of swamps and floodplains in which the Cauca, San Jorge, and Magdalena rivers drain their waters (8). The department of Sucre occupies an area of the Mojana region, which is located in the south, and the municipality of San Marcos is located there, which has numerous bodies of water (9), which are reservoirs of a huge diversity of aquatic fauna that plays a fundamental ecological role (10), and in turn represents an important food source for the inhabitants of this territory. The soils and waters of San Marcos have been contaminated through the waters of the San Jorge River, which receives water and sediments contaminated with heavy metals from the other rivers that surround La Mojana, in whose basins the exploitation of ferronickel and gold occurs (11).

Various studies of Hg contamination have been carried out in the area in several environmental compartments. In a study, Pinedo-Hernández et al (6) determined the presence of mercury in sediments, registering T-Hg concentrations between 196.2 and 1187.6 ng/g and an average of 524.2±256.8 ng/g (6). Another research recorded mean values of T-Hg in fish of 0.223±0.027 µg/g in hair, a concentration range between 0.17 - 8.8 µg/g, and in sediments of 0.097±0.049 µg/g (7). Buelvas-Soto et al (8) determined the Hg levels in 47 samples of blood and feathers from the duck Dendrocygna autumnalis, registering high Hg values in these birds that reside in the La Mojana wetlands. Marrugo-Negrete et al (12) determined concentrations of mercury and methylmercury (MeHg) in the 10 most consumed fish species in 11 municipalities of La Mojana, obtaining concentration ranges between 0.22-0.58 µg/g in carnivorous fish. Marrugo-Negrete et al (13) determined T-Hg concentrations in fish, the highest being in the carnivore *Pseudoplatystoma fasciatum*, and the lowest in the non-carnivore *Prochilodus magdalenae* (13).

For this reason, the current research focuses on the study of the presence of Hg in the ichthyofauna of La Mojana and the most relevant impacts on the health of the inhabitants of the area.

The purpose of this research was to determine the concentrations of T-Hg in the eleven fish species most consumed in the municipality of San Marcos - Sucre.

MATERIALS AND METHODS

Study area. The samplings were carried out in six bodies of water around San Marcos (latitude 8° 35’ 06’’ N-Longitude, 75° 07’ 16.39’’ W) in Mojana Sucreña. The sampling areas were Ciénaga de San Marcos, Caño Carate, Caño

Viloria, Río San Jorge, Ciénaga de Belén, and Ciénaga de Palo Alto. San Marcos is located in the La Mojana ecoregion, a highly biodiverse area located on the Caribbean coast of Colombia that serves as drainage area for three large Colombian rivers: Magdalena, Cauca, and San Jorge. These three rivers transport metals and other pollutants products of mining and agricultural activity through their basins. The Mojana wetlands are a reservoir of great biodiversity and provide fundamental ecosystem services (7) (Figure 1).

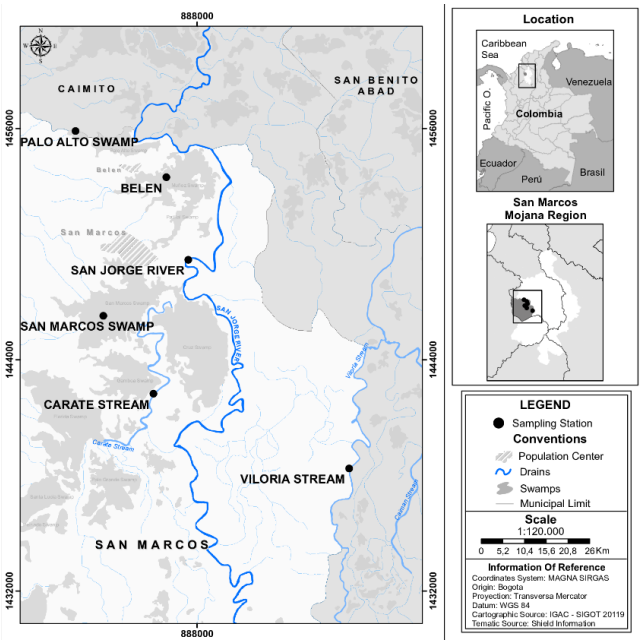

Figure 1. Mojana Sucreña. Sampling points 1. Palo Alto Swamp 2. Belén Swamp. 3. San Jorge River 4. San Marcos Swamp 5. Carate stream. 6. Viloria Stream.

Collection of samples. The samplings were developed during the month of June 2017. To determine the fish species with the highest consumption in the municipality, surveys were applied to the inhabitants about their consumption habits and later, the capture of the species was carried out in the bodies of water from the municipal seat and in the rural area of San Marcos, with the help of local fishermen (n=110), 10 individuals per species. The species of interest identified for this study were: *Pseudoplatystoma magdaleniatum, Plagioscion surinamensis, Hoplias malabaricus, Sorubim cuspicaudus, Ageneiosus pardalis, Petenia kraussi, Leporinus muyscorum, Triportheus magdalenae, Prochilodus magdalenae, Pimelodus clarias* y *Curimata magdalenae*. The catches were made with the help of local fishermen in the habitats of the studied species, using their traditional fishing tools. The entrails were extracted from the captured fish individually packed in labeled plastic bags, which were transported in a cold chain to the Water, Applied, and Environmental Chemistry laboratory of the Universidad de Córdoba. T-Hg was quantified in samples taken from the dorsal muscle of the captured fish. The fish species studied were identified using the taxonomic keys of The Red Book of Freshwater Fishes of Colombia (14).

Sample analysis. Using cold vapor atomic absorption spectrophotometry (CVAAS), T-Hg levels were quantified in the dorsal muscle of fish using a DMA-80 Milestone mercury determination system (15). The extracted samples were digested using a mixture of H_2SO_4 -HNO_3 2:1 v/v at a temperature of 100°C for 3 hours, using 0.5 g in the process for the analysis of T-Hg. The detection limit was 0.001 µg/g calculated as the mean plus three (3) times the standard deviation (SD). The quality control of the method was done with certified reference material for fish (IAEA – 407; 0.222 ± 0.6 µg/g). The recovery percentage was 98.6 ± 0.35%. The T-Hg results were expressed in µg/g.

Statistical analysis. The statistical treatment was carried out from the calculation of the mean concentrations (± standard deviation) of T-Hg in the muscle of each species studied. In this way, the Kolmogorov-Smirnov test verified the normality of the distribution of T-Hg levels. Subsequently, the homogeneity of the sample variances was evaluated using the Bartlett Test and an ANOVA was performed using the Tukey test to determine whether or not there were significant differences in the distribution of T-Hg in the muscle of the fish studied, always using a significance level of 95% ($p<0.05$). Data treatment was developed with the statistical packages Statgraphics centurion version 15.2.06 and Infostat3.

RESULTS

The mean values of T-Hg in the 11 species studied are recorded in Table 1. In this sense, *Pseudoplatystoma magdaleniatum* presented the highest average levels of Hg in the evaluated tissue, while *Curimata magdalenae*, presented the lowest concentrations of Hg. Regarding the

consumption of the studied species, the species most consumed by the population under study was *Prochilodus magdalenae*, while the least consumed species was *Ageneiosus pardalis*. Regarding the eating habits of the studied species, the species with carnivorous habits were the ones that bioaccumulated the most Hg (0.44±0.09 µg/g), while the non-carnivorous species presented mean concentrations of this metal that were relatively lower (0.19 ± 0.04 µg/g).

Figures 2, 3, and 4 illustrate the differences in the distributions of the mean T-Hg values in the fish studied by species, according to their eating habits and trophic levels, respectively.

Table 1. Mean values of T-Hg (µg/g) in the fish with the highest consumption in San Marcos with the trophic level, feeding habits, type of migration, and average weekly consumption (g/week).

Common name	Scientific name	Trophic level	Feeding habits	Type of migration	Average consumption (g/week)	Mean concentration ±SD (µg/g^{-1})
Bagre pintado	*Pseudoplatystoma magdaleniatum*	SC	P-C	MM	97.92	0.44 ± 0.09
Pacora	*Plagioscion surinamensis*	SC	P-C	MM	49.85	0.42 ± 0.14
Moncholo	*Hoplias malabaricus*	SC	P-C	NM	101.39	0.39 ± 0.11
Bagre blanquillo	*Sorubim cuspicaudus*	SC	P-C	MM	131.81	0.37 ± 0.07
Doncella	*Ageneiosus pardalis*	SC	P-C	SM	14.32	0.35 ± 0.04
Mojarra Amarilla	*Petenia kraussii*	SC	P-C	NM	59.64	0.19 ± 0.04
Comelón	*Leporinus muyscorum*	PC	NC-O	SM	82.92	0.13 ± 0.01
Arenca	*Triportheus magdalenae*	SC	Z-C	NM	35.002	0.11 ± 0.01
Bocachico	*Prochilodus magdalenae*	PC	NC-D	MM	504.57	0.11 ± 0.01
Barbudo	*Pimelodus clarias*	SC	NC-O	LM	47.93	0.10 ± 0.02
Viejito	*Curimata magdalenae*	PC	NC-D	SM	78.43	0.07 ± 0.01

SC: Secondary consumer. PC: Primary consumer. P-C: Piscivorous carnivore. Z-C: Zooplanctophage Carnivore. NC-O: Non carnivore omnivore. NC-D: Non carnivorous detritivore. SM: short migration. MM: Medium migration. LM: Large migration. NM: Non-migratory.

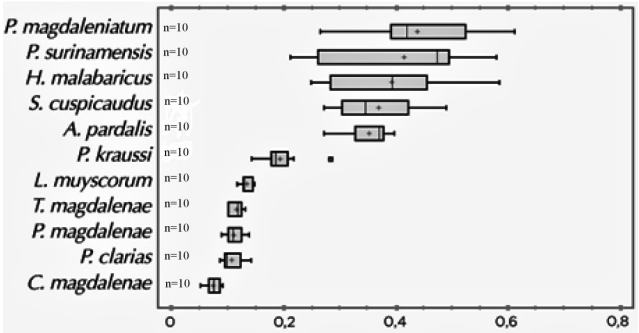

Figure 2. Distribution of the mean levels of T-Hg (µg/g) in the fish species studied

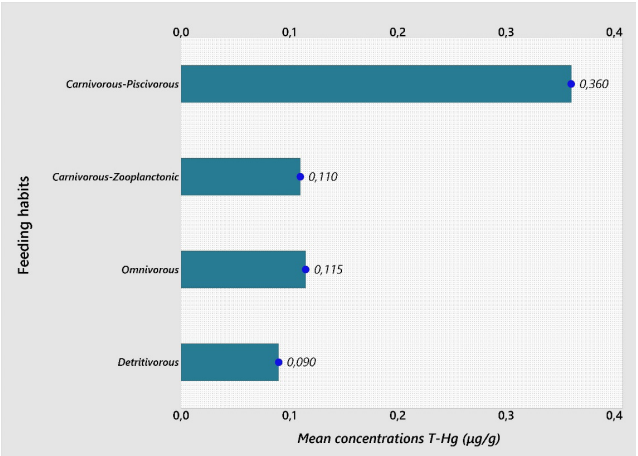

Figure 3. Variability of the mean concentrations of T-Hg (µg/g) according to the eating habits of the fish species consumed in the municipality of San Marcos.

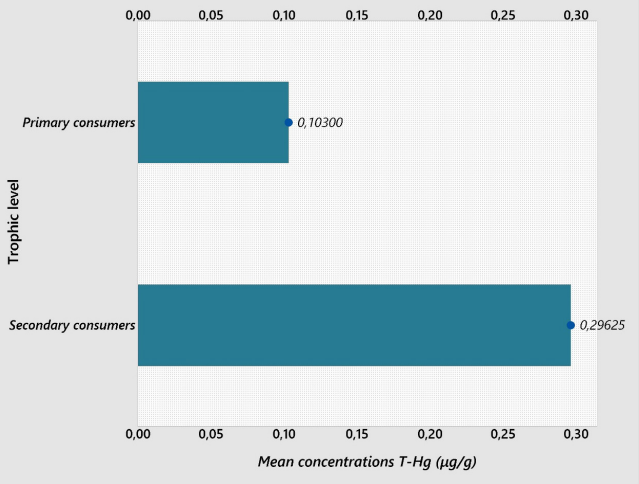

Figure 4. Variability of the mean concentrations of T-Hg (µg/g) according to the trophic levels of the fish species consumed in the municipality of San Marcos.

DISCUSSION

Among the fish species studied, *P. magdalenae*, *S. cuspicaudus,* and *H. malabaricus* are the ones with the highest consumption in the area (12). *P. magdalenae* and *S. cuspicaudus* are endemic to Colombia, and of great acceptance and commercial value. *P. magdalenae* is fished and consumed constantly throughout the year (16), and for a few decades, a high pressure has been exerted on this species due to its excessive exploitation, being currently the main species in the municipality's artisanal fishing (12). On the other hand, *S. cuspicaudus* is a rheophilic fish that travels long distances in schools, making two migrations annually, one reproductive or climbing, and the other trophic or low (17); within its genus, it is considered the largest species, reaching up to 80 cm in standard length, which makes it ideal for human consumption (18). On the other hand, *H. malabaricus* is a neotropical fish that has a wide geographical distribution, present in almost all the hydrographic basins of South America, except the trans-Andean area of the rivers of Patagonia (19). This species has the ability to adapt to various aquatic ecosystems, including estuarine ones, which makes it a valuable fishery resource (20).

The highest levels of T-Hg were quantified in species with carnivorous habits, which may be due to the fact that they feed on smaller fish, since these species occupy high links in the trophic networks of the bodies of water they inhabit (7), which encourages heavy metals, such as mercury to bioaccumulate and biomagnify more efficient and significantly (21,22). On the other hand, the lowest levels of T-Hg were recorded in detrivorous fish showing indirect phytoplanktonic habits, which could explain the lower rate of mercury bioaccumulation in the dorsal muscle (23). In particular, species such as *L. muyscorum* have omnivorous eating habits with an herbivorous tendency (24). On the other hand, *T. magdalenae* has a carnivorous-zooplanktonic diet (25). Therefore, it is possible that the permanent interaction with sediments, in which high concentrations of mercury are generally deposited and accumulated (26) is the cause of mercury contamination in this important species, which is consumed due to its great abundance, ease of capture, and low commercial cost (27).

The variance analyzes carried out show significant variability ($p<0.05$) in the bioaccumulation rates and mercury distribution in the studied species and their several niches and habitats. From this, it is shown that carnivorous fish accumulate higher concentrations of Hg, which is in accordance with that reported by Marrugo et al. (28), in a study carried out in the Urrá reservoir (Córdoba), in which the carnivorous species *Hoplias malabaricus* presented the highest mercury values (1.39 ± 0.69 µg/g), while the non-carnivorous-detrivorous species *Curimata magdalenae*, as in this research presented the lowest Hg concentrations (0.15 ± 0.02 µg/g). In a study carried out in the Ayapel swamp (13), the highest mercury values were presented by the carnivorous species *Pseudoplatystoma fasciatum* (0.432 ± 0.107 µg/g), while the non-carnivorous species *P. magdalenae* presented the lowest concentration (0.143 ± 0.053 µg/g). Another study carried out in 11 municipalities of La Mojana evaluated the levels of mercury and MeHg in the 10 most consumed fish species, determining that the highest values of mercury and MeHg were recorded in carnivorous species, such as *C. kraussii*, *S. cuspicaudus* and *A. pardalis* (12).

At this point, it is necessary to understand the mobility and displacement regimes of the studied species to understand the accumulation processes, contamination, and mercury toxicity in aquatic ecosystems (29). *P. magdaleniatum*, *S. cuspicaudus,* and *Plagioscion surinamensis* are cataloged as migratory species. Their reproductive habits induce them to travel in search of suitable places to carry out this vital function (30). It has been recorded that, in

the places of origin of these species, there are places where considerable concentrations of Hg are present in various environmental matrices (7), particularly in the Viloria channel, where contamination is relatively high (31). The second group in which *T. magdalenae* and *C. magdalenae* are classified as species that perform their vital functions mainly in swamps have a lower relative mobility regime, and consequently, a lower probability of presenting significant variations in Hg contamination processes (32).

There are two exceptions that must be taken into account: the first corresponds to *P. clarias* and *P. magdalenae*, which are migratory species. However, the analyzes showed low concentrations and variability in the Hg accumulation processes; and the second corresponds to *H. malabaricus*, which is a non-migratory species, but which has a high concentration and variability of Hg. These particular cases may occur because, in addition to the trophic position and the mobility regime of the species, there are other factors that determine the bioaccumulation and biomagnification processes of Hg, such as the type of tissue in which it accumulates, the species, age, sex, weight, length, temperature, microbial biomass activity, salinity, pH, and oxidation potential-reduction of the water mass (33).

Regarding the toxicity of Hg in the species studied, a series of serious and acute effects have been reported on the health and integrity of contaminated individuals (34,35). Among the characteristic adverse effects of Hg intoxication in fish, there are nervous, motor, behavioral, reproductive, hematological, and metabolic alterations and dysfunctions (36,37). Consequently, the frequent consumption of fish contaminated with Hg generates serious alterations in human health (12,38), since the great majority of the Hg that enters the human body through the consumption of contaminated fish species does so, in the form of methylmercury (MeHg) and dimethylmercury (DMHg) (38), which enhances and maximizes the toxicological capacity of this heavy metal in the body, since these bioactivated forms of Hg have a high affinity with the molecular and tissue component of the human body, generating cytotoxicity and genotoxicity (39), as well as serious neurological and hematic alterations (40).

Although none of the species studied presented mean concentrations of Hg above the maximum value established by the WHO (0.5 µg/g), the consumption habits of the surveyed residents of the municipality of San Marcos represent a potential long-term risk, since Hg has a high toxicity, even when it is consumed in low doses for long periods of time (41).

It is concluded that the most consumed fish in San Marcos are contaminated with Hg, a product of mining that occurs upstream, which discharges its residues in La Mojana. This represents a risk for the fish assemblages and the inhabitants of the area who feed on them. Constant monitoring of Hg contamination levels in the area and environmental policies are recommended to avoid the excessive dumping of heavy metals in this region.

Feeding fish meat contaminated with mercury is a risk to public health in this region, which is why educating the populations of La Mojana about the consumption of these fish is necessary in order to protect pregnant women, children, and adults about the damages that Hg can cause.

Conflict of Interest

None of the authors have conflicts of interest.

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REFERENCES

1. Beckers F, Rinklebe J. Cycling of mercury in the environment: Sources, fate, and human health implications: A review. Crit Rev Environ Sci Technol. 2017; 47(9):693–794. https://doi:10.1080/10643389.2017.1326277

2. Niane B, Guédron S, Feder F, Legros S, Ngom PM, Moritz R. Impact of recent artisanal small-scale gold mining in Senegal: Mercury and methylmercury contamination of terrestrial and aquatic ecosystems. Sci Total Environ. 2019; 669:185–9.https://doi:10.1016/j.scitotenv.2019.03.108

3. Okpala COR, Sardo G, Vitale S, Bono G, Arukwe A. Hazardous properties and toxicological update of mercury: From fish food to human health safety perspective. Crit Rev Food Sci Nutr. 2018; 58(12):1986–2001. https://doi:10.1080/10408398.2017.1291491

4. P Li, Du B, Chan HM, Feng X. Human inorganic mercury exposure, renal effects and possible pathways in Wanshan mercury mining area, China. Environ Res. 2015; 140:198–204. https://doi.org/10.1016/j.envres.2015.03.033

5. Lavoie RA, Jardine TD, Chumchal MM, Kidd KA, Campbell LM. Biomagnification of mercury in aquatic food webs: a worldwide meta-analysis. Environ Sci Technol. 2013; 47(23):13385–13394. https://doi.org/10.1021/es403103t

6. Pinedo-Hernández J, Marrugo-Negrete J, Díez S. Speciation and bioavailability of mercury in sediments impacted by gold mining in Colombia. Chemosphere. 2015; 119:1289–1295. https://doi.org/10.1016/j.chemosphere.2014.09.044

7. Marrugo Negrete J, Pinedo-Hernández J, Paternina-Uribe R, Quiroz-Aguas L, Pacheco-Florez S. Distribución espacial y evaluación de la contaminación ambiental por mercurio en la región de la Mojana, Colombia. Rev MVZ Cordoba. 2018; 23(S):7062–7075. https://doi.org/10.21897/rmvz.1481

8. Buelvas-Soto J, Marrugo-Madrid S, Marrugo-Negrete J. Bioacumulación de mercurio y plomo en el pato Dendrocygna autumnalis en la subregión de la Mojana, Colombia.Rev MVZ Córdoba. 2022; 27(1):e2337. https://doi.org/10.21897/rmvz.2337

9. Isaacs Cubides P. Rehabilitación del ecosistema de humedal en la región de la Mojana para mitigar efecto de las inundaciones. Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt; 2020. http://repository.humboldt.org.co/handle/20.500.11761/35508

10. Evenson GR, Golden HE, Lane CR, McLaughlin DL, D'Amico E. Depressional wetlands affect watershed hydrological, biogeochemical, and ecological functions. Ecol Appl. 2018; 28(4):953–966. https://doi:10.1002/eap.1701

11. Marrugo-Negrete J, Pinedo-Hernández J, Marrugo-Madrid S, Díez S. Assessment of trace element pollution and ecological risks in a river basin impacted by mining in Colombia. Environ Sci Pollut Res Int. 2021; 28(1):201–210. https://doi.org/10.1007/s11356-020-10356-4

12. Marrugo-Negrete J, Vargas-Licona S, Ruiz-Guzmán JA, Marrugo-Madrid S, Bravo AG, Díez S. Human health risk of methylmercury from fish consumption at the largest floodplain in Colombia. Environ Res. 2020; 182(109050):109050. https://doi.org/10.1016/j.envres.2019.109050

13. Marrugo-Negrete J, Benítez LN, Olivero-Verbel J, Lans E, Vazquez Gutierrez F. Spatial and seasonal mercury distribution in the Ayapel Marsh, Mojana region, Colombia. Int J Environ Health Res. 2010; 20(6):451–459. https://DOI:10.1080/09603123.2010.499451

14. Mojica JI, Vélez JCC. Libro rojo de peces dulceacuícolas de Colombia. 1st ed. Bogotá: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt; 2012. http://hdl.handle.net/20.500.11761/34197

15. Sadiq M, Zaidi TH, Al-Mohana H. Sample weight and digestion temperature as critical factors in mercury determination in fish. Bull Environ Contam Toxicol. 1991; 47(3):335–341. https://doi: 10.1007/BF01702191

16. Atencio G V, Kerguelén D E, Naar E, Petro R. Desempeño reproductivo del bocachico Prochilodus magdalenae inducido dos veces en un mismo año. Rev MVZ Cordoba. 2013; 18(1):3304–3310. https://doi.org/10.21897/rmvz.192

17. Jiménez-Segura LFF, Palacio J, López R. Características biológicas del blanquillo Sorubim cuspicaudus littmann; Burr y Nass, 2000 y Bagre rayado Pseudoplatystoma magnaleniatumBuitrago-Suárez y Burr, 2007 (Siluriformes: Pimelodidae). Actual Biol. 2009; 31(90):1–14. https://revistas.udea.edu.co/index.php/actbio/article/view/4729

18. Buendía Lara D, Argumedo Díaz J, Olaya-Nieto C, Segura-Guevara F, Brú-Cordero S, Tordecilla-Petro G. Biología reproductiva del blanquillo (Sorubim cuspicaudus Littmann et al., 2000) en la cuenca del Río Sinú, Colombia. Rev MVZ Cordoba. 2006; 11(S):71–78. https://doi.org/10.21897/rmvz.1046

19. Ibagón N, Maldonado-Ocampo JA, Cioffi M de B, Dergam JA. Chromosomal diversity of Hoplias malabaricus (Characiformes, erythrinidae) along the Magdalena river (Colombia—northern south America) and its significance for the neotropical region. Zebrafish. 2020; 17(3):211–219. https://doi.org/10.1089/zeb.2019.1827

20. Guimarães CBS, Pflanzer Junior SB, Pinheiro HP, Mendes TMF, Ueta MT. Centesimal composition and meat yield of Hoplias malabaricus: association with intestinal parasites. Braz J Vet Parasitol. 2021; 30(1):e021120. https://doi.org/10.1590/S1984-29612021020

21. Salazar-Camacho C, Salas-Moreno M, Paternina-Uribe R, Marrugo-Negrete J, Díez S. Mercury species in fish from a tropical river highly impacted by gold mining at the Colombian Pacific region. Chemosphere. 2021; 264(Pt 2):128478. https://doi.org/10.1016/j.chemosphere.2020.128478

22. Azevedo-Silva CE, Almeida R, Carvalho DP, Ometto JPHB, de Camargo PB, Dorneles PR, et al. Mercury biomagnification and the trophic structure of the ichthyofauna from a remote lake in the Brazilian Amazon. Environ Res. 2016; 151:286–296. https://doi.org/10.1016/j.envres.2016.07.035

23. Mille T, Bisch A, Caill-Milly N, Cresson P, Deborde J, Gueux A, et al. Distribution of mercury species in different tissues and trophic levels of commonly consumed fish species from the south Bay of Biscay (France). Mar Pollut Bull. 2021; 166(112172):112172. https://doi.org/10.1016/j.marpolbul.2021.112172

24. Segura-Guevara F, López-Corrales H, Medrano De La Hoz C, Olaya-Nieto CW. Biología reproductiva de Liseta Leporinus muyscorum Steindachner, 1901 en el río Sinú, Colombia. Rev MVZ Cordoba. 2017; 22(1):5728–5737. https://doi.org/10.21897/rmvz.932

25. Morales J, García-Alzate CA. Ecología trófica y rasgos ecomorfológicos de Triportheus magdalenae (Characiformes: Triportheidae) en el embalse El Guájaro, cuenca baja del río Magdalena, Colombia. Rev Biol Trop. 2018; 66(3):1208. https://doi.org/10.15517/rbt.v66i3.30621

26. Paranjape AR, Hall BD. Recent advances in the study of mercury methylation in aquatic systems. Facets (Ott). 2017; 2(1):85–119. https://doi.org/10.1139/facets-2016-0027

27. Valdelamar Villegas JC. Apuntes sobre la importancia ecológica, ambiental y social de la arenca Triportheus magdalenae (Steindachner, 1878). Un ejemplo de endemismo invisibilizado. Intropica. 2018; 13(2):152-165. https://doi.org/10.21676/23897864.2628

28. Marrugo-Negrete J, Navarro-Frómeta A, Ruiz-Guzmán J. Total mercury concentrations in fish from Urrá reservoir (Sinú river, Colombia). Six years of monitoring. Rev MVZ Cordoba. 2015; 20(3):4754–4765. https://doi.org/10.21897/rmvz.45

29. Qian Y, Cheng C, Feng H, Hong Z, Zhu Q, Kolenčík M, et al. Assessment of metal mobility in sediment, commercial fish accumulation and impact on human health risk in a large shallow plateau lake in southwest of China. Ecotoxicol Environ Saf. 2020; 194(110346):110346. https://doi.org/10.1016/j.ecoenv.2020.110346

30. López-Casas S, Jiménez-Segura LF, Agostinho AA, Pérez CM. Potamodromous migrations in the Magdalena River basin: bimodal reproductive patterns in neotropical rivers: Potamodromous migrations in the magdalena river basin. J Fish Biol. 2016; 89(1):157–171. https://doi.org/10.1111/jfb.12941

31. Argumedo G, Marcela P, Vergara C, Vidal JV, Marrugo-Negrete J. Evaluación de la concentración de mercurio en arroz (Oryza sativa) crudo y cocido procedente del municipio de San Marcos- Sucre y zona aurífera del municipio de Ayapel – Córdoba. Rev Univ Ind Santander. 2015; 47(2):169-177. https://revistas.uis.edu.co/index.php/revistasaluduis/article/view/4826

32. Zapata L, Usma J. Guía de las especies Migratorias de la Biodiversidad en Colombia. Peces. Ministerio de Ambiente y Desarrollo Sostenible / WWF-Colombia. Bogotá, D.C. Colombia; 2013. https://wwflac.awsassets.panda.org/downloads/migratoriaspeces_42_web_final.pdf

33. Li H, Zheng D, Yang J, Wu C, Zhang S, Li H, et al. Salinity and redox conditions affect the methyl mercury formation in sediment of Suaeda heteroptera wetlands of Liaoning province, Northeast China. Mar Pollut Bull. 2019; 142:537–543. https://doi.org/10.1016/j.marpolbul.2019.03.066

34. Monteiro DA, Taylor EW, Rantin FT, Kalinin AL. Impact of waterborne and trophic mercury exposures on cardiac function of two ecologically distinct Neotropical freshwater fish Brycon amazonicus and Hoplias malabaricus. Comp Biochem Physiol C Toxicol Pharmacol. 2017; 201:26–34. https://doi.org/10.1016/j.cbpc.2017.09.004

35. Morcillo P, Angeles Esteban M, Cuesta A. Mercury and its toxic effects on fish. AIMS Environ Sci. 2017; 4(3):386–402. https://doi.org/10.3934/environsci.2017.3.386

36. Sun Y, Li Y, Rao J, Liu Z, Chen Q. Effects of inorganic mercury exposure on histological structure, antioxidant status and immune response of immune organs in yellow catfish (Pelteobagrus fulvidraco): Mercury induces oxidative stress and immune response in immune organs. J Appl Toxicol. 2018; 38(6):843–54. https://doi.org/10.1002/jat.3592

37. Pereira P, Korbas M, Pereira V, Cappello T, Maisano M, Canário J, et al. A multidimensional concept for mercury neuronal and sensory toxicity in fish - From toxicokinetics and biochemistry to morphometry and behavior. Biochim Biophys Acta Gen Subj. 2019; 1863(12):129298. https://doi.org/10.1016/j.bbagen.2019.01.020

38. Olivero-Verbel J, Carranza-Lopez L, Caballero-Gallardo K, Ripoll-Arboleda A, Muñoz-Sosa D. Human exposure and risk assessment associated with mercury pollution in the Caqueta River, Colombian Amazon. Environ Sci Pollut Res Int. 2016; 23(20):20761–20771. https://doi.org/10.1007/s11356-016-7255-3

39. Calao CR, Marrugo JL. Efectos genotóxicos en población humana asociados a metales pesados en la región de La Mojana, Colombia, 2013. Biomedica. 2015; 35(S2). https://doi.org/10.7705/biomedica.v35i0.2392

40. Rice KM, Walker EM Jr, Wu M, Gillette C, Blough ER. Environmental mercury and its toxic effects. J Prev Med Public Health. 2014; 47(2):74–83. https://doi.org/10.3961/jpmph.2014.47.2.74

41. Oliveira LF, Rodrigues LD, Cardillo GM, Nejm MB, Guimarães-Marques M, Reyes-Garcia SZ, et al. Deleterious effects of chronic mercury exposure on in vitro LTP, memory process, and oxidative stress. Environ Sci Pollut Res Int. 2020; 27(7):7559–7569. https://doi.org/10.1007/s11356-019-06625-6