Negative impacts of mining on Neotropical freshwater fishes

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Mining activities have significantly affected the Neotropical freshwater ichthyofauna, the most diverse in the world. However, no study has systematized knowledge on the subject. In this review, we assembled information on the main impacts of mining of crude oil, gold, iron, copper, and bauxite on aquatic ecosystems, emphasizing Neotropical freshwater fishes. The information obtained shows that mining activities generate several different disturbances, mainly via input of crude oil, metals and other pollutants, erosion and siltation, deforestation, and road construction. Mining has resulted in direct and indirect losses of fish diversity in several Neotropical waterbodies. The negative impacts on the ichthyofauna may change the structure of communities, compromise entire food chains, and erode ecosystem services provided by freshwater fishes. Particularly noteworthy is that mining activities (legal and illegal) are widespread in the Neotropics, and often located within or near protected areas. Actions to prevent and mitigate impacts, such as inspection, monitoring, management, and restoration plans, have been cursory or absent. In addition, there is strong political pressure to expand mining; if – or when – this happens, it will increase the potential of the activity to further diminish the diversity of Neotropical freshwater fishes.

Keywords: Deforestation, Mercury, Oil spill, Roads, Silting.

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As atividades de mineração têm impactado significativamente a ictiofauna de água doce Neotropical, a mais diversa do mundo. Porém, nenhum estudo sistematizou o conhecimento sobre o assunto. Nesta revisão, reunimos informações sobre os principais impactos da mineração de petróleo, ouro, ferro, cobre, e bauxita sobre os ecossistemas aquáticos, com ênfase nos peixes de água doce Neotropicais. As informações obtidas mostram que as atividades de mineração geram diferentes distúrbios, principalmente por meio de petróleo bruto, metais e outros poluentes, erosão e assoreamento, desmatamento e construção de estradas. A mineração resultou em perda direta e indireta de diversidade de peixes de vários corpos d'água Neotropicais. Os impactos negativos sobre a ictiofauna podem alterar a estrutura das comunidades, comprometer cadeias alimentares inteiras, bem como degradar os serviços ecossistêmicos fornecidos pelos peixes de água doce. Particularmente importante é que as atividades de mineração (legais e ilegais) são generalizadas na região Neotropical, e frequentemente estão localizadas dentro ou perto de áreas protegidas. Ações de prevenção e mitigação de impactos, como planos de fiscalização, monitoramento, manejo e restauração, têm sido precárias ou ausentes. Além disso, há forte pressão política para expandir a mineração; se – ou quando – isso acontecer, aumentará o potencial da atividade em diminuir ainda mais a diversidade de peixes de água doce Neotropicais.

Palavras-chave: Assoreamento, Derramamento de óleo, Desmatamento, Estradas, Mercúrio.

INTRODUCTION

The Neotropical realm supports the greatest known diversity of freshwater fish in the world, including over 6,000 described species (Albert *et al*., 2020). These fishes vary considerably in length, from mere centimeters to meters (Ferraris Jr., 2003; Castro, Polaz, 2020), and they display complex biogeographic patterns at multiple spatial extents. Freshwater fishes from the Neotropical region also display disproportionally high functional diversity (Toussaint *et al*., 2016), perform critical ecological functions (Reys *et al*., 2009), and provide many important ecosystem services, particularly artisanal and commercial fisheries (*e.g*., Isaac *et al*., 2015). Fish are also used in countless products such as jewelry and other objects (Olden *et al*., 2020), contribute to medicinal treatments (Alves, Rosa, 2006), and provide many other services. This rich biodiversity, however, has been eroded, degraded, or threatened with extinction (Reis *et al*., 2016; Pelicice *et al*., 2017; Vitule *et al*., 2017; ICMBio, 2018).

Mining is one of several activities that have affected Neotropical fish diversity (Pelicice *et al*., 2017). Mining extracts various materials (*e.g*., sand, oil, metals) and is conducted near or within waterbodies, generating a variety of wide-ranging negative consequences. For instance, successive oil spills from petroleum wells or pipelines in the Amazon basin (especially in Peru) have damaged fish assemblages in several rivers (Azevedo-Santos *et al*., 2016; Fraser, 2016). Another emblematic example was the recent rupture of tailings dams in southeastern Brazil, when toxic mine waste flowed into the Doce River and dramatically affected fish diversity (Fernandes *et al*., 2016; Weber *et al*., 2020). These are just a few examples of how mine operations and failures negatively affect freshwater ecosystems, including large-scale fish kills and biodiversity losses. Despite recent catastrophes that expose the dangers of mining operations (*e.g*., Fernandes *et al*., 2016; Olden *et al*., 2019), many Neotropical nations have largely downplayed the negative and pervasive impacts of mining. This is certainly the case for Brazil, where mining is widespread and plans exist for expansion and changes in legislation favoring the mining sector (Meira *et al*., 2016; Congresso Nacional, 2020).

The science to inform mining policy in the Neotropical region is available in published journals, grey literature (often internal mining company reports), and the news media, yet it has not been synthesized to facilitate an understanding of mining impacts on the Neotropical ichthyofauna. To address this knowledge gap, we systematically reviewed current knowledge regarding the main negative impacts of mining on Neotropical freshwater fishes. Several types of mining have related consequences. For example, gold mining results in input of toxic metals (*e.g*., Malm, 1998), which also occurs with petroleum production (*e.g*., Baqué, Doyle, 2017). Thus, we list the main impacts of mining of crude oil, gold, iron, copper, and bauxite. We chose these ores because there is more available information of negative impacts related to them. Although the negative effects of mining can be pervasive across taxonomic groups (*e.g*., Callisto *et al*., 1998a; Brosse *et al*., 2011), in this review we explore the impacts that can arise from inputs of crude oil and heavy metals and other pollutants, sediment erosion and siltation, deforestation practices, and road construction on Neotropical freshwater fishes.

MAIN CONSEQUENCES AND NEGATIVE IMPACTS ON FISHES

Mining is a necessary activity for human societies. We depend on petroleum for transporting people and commodities, for example, and metals are a key component of human civilizations. However, mining has also proven to cause countless negative environmental impacts (*e.g*., Callisto *et al*., 1998a,b; Brosse *et al*., 2011; Hughes *et al*., 2016; Marrugo-Negrete *et al*., 2018; Albuquerque *et al*., 2020) that can be avoided or minimized. In this section, we review how different mining activities lead to detrimental impacts on Neotropical freshwater fishes.

Input of crude oil. Oil extraction and transportation are major economic activities, and oil spills resulting from poor mining practices are not uncommon (*e.g*., Sebastián, Hurtig, 2004; Hughes *et al*., 2016). Crude oil spills in Neotropical waterbodies have occurred repeatedly during or after the extraction (in the blocks) or in the transport via pipelines, latter associated with human actions (*e.g*., vandalism – including terrorism, poor maintenance) or environmental sources (*i.e*., natural catastrophes). In the Peruvian Amazon alone, more than 400 leaks were recorded over 19 years (León, Zúñiga, 2020), and many hundreds more occurred but were not reported or even discovered. The scenario is more complicated if we consider other countries (*e.g*., Ecuador) that extract oil in the region. Most instances of oil spills are poorly documented in the scientific literature, and effects on fish assemblages are substantially underreported. In addition to accidental spill events, crude oil was also intentionally released into ecosystems, likely reaching freshwater ones (Kimerling, 2006).

The environmental implications of oil spills on Neotropical freshwater fishes remain poorly documented (*e.g.*, Fraser, 2016). However, in the Amazon basin, oil spills are frequent, resulting in dramatic impacts to fish assemblages (Fig. 1). Several oil spills have caused fish mortality (see Tab. 1) and have led to the accumulation of crude oil in organisms and in the freshwater environments (*e.g.*, Fig. 1). The Marañón River basin, an important region for fishing (Coomes *et al*., 2010), has been the recipient of successive crude oil spills that have killed many fishes (Tab. 1).

The negative impacts of oil spills directly or indirectly related to petroleum activities extend beyond the Amazon River basin. A highly damaging case occurred in Brazil, where a crude oil spill was dumped in a stream, later reached the Barigui River, and flowed to the Iguaçu River (South Brazil), resulting in massive mortality (Tab. 1; see also Ostrensky *et al*., 2003). The Iguaçu River is the main waterbody of the Iguaçu River basin, where more than 50% of fish species are endemic (Zawadzki *et al*., 1999). Thus, oil spills in these Neotropical ecosystems (*e.g.*, Iguaçu, Amazon basins) have probably impacted several endemic fish species, including those not described yet. Even in cases where there is no clear evidence of impacts on fish diversity (*e.g.*, in Tab. 1), they possibly occurred at some level. For example, Short (2003) argued that oil contains the life-damaging chemicals "polycyclic aromatic hydrocarbons (PAH)", and that these compounds negatively affect salmonid embryogenesis. In general, exposure to crude oil can have different non-lethal effect, such as impairing swimming capacity, and can result in malformations (Carls *et al*., 1999). Studies also show that fish exposed to petroleum have become more susceptible to parasitism (Khan, 1990) and eye and cardiac dysfunctions (Cherr *et al*., 2017; Magnuson *et al*., 2020). Thus, oil spills will not always have immediately visible effects on fishes, but they can affect individuals and populations for a long time.

TABLE 1 | Reports on crude oil spills in Neotropical waterbodies – also including those with negative impacts on fish diversity (based on Methods and Search results in **S1A** and **S1B**, respectively).

Waterbodies	Country	Year of spill	Amount (liters)	Negative impacts on fish diversity
Andean River to Lake Titicaca	Bolivia	2000	~4,734,642	Yes
Stream to the Barigui and after to the Iguaçu River	Brazil	2000	~4,000,000	Yes
Catatumbo River to Lake Maracaibo	Colombia (effects in Venezuela)	2001	~2,861,771	Possibly
Coatzacoalcos River	Mexico	2004	~794,937	Possibly
Coatzacoalcos River	Mexico	2011	~238,481	Yes
Catatumbo River to Lake Maracaibo	Colombia (effects in Venezuela)	2012	Unknown	Yes
Guarapiche River	Venezuela	2012	~10,175,204 to ~19,078,508	Yes
Coca River	Ecuador (effects in Peru)	2013	~1,825,174	Possibly
Lake - Unknown name	Peru	2014	Unknown	Yes
A tributary of the Marañón River basin	Peru	2014	~254,380	Yes
Stream - Unknown name	Peru	2014	Unknown	Yes
Stream - Unknown name	Brazil	2015	~600	Possibly
Chiriaco and Morona Rivers - 1	Peru	2016	~476,962	Possibly
Chiriaco and Morona Rivers - 2	Peru	2016	Unknown	Possibly
Stream - Unknown name	Peru	2016	Unknown	Possibly
Tepeyac stream and Coatzacoalcos River	Mexico	2018	Unknown	Yes
Streams, Sogamoso and Magdalena Rivers	Colombia	2018	~79,494 to ~87,443	Yes
Coca and Napo Rivers	Ecuador (effects in Peru)	2020	~2,384,809	Yes
Godineau River	Trinidad and Tobago	2020	Unknown	Possibly
Shiripuno River	Ecuador	2020	Unknown	Possibly

FIGURE 1 | Dead fishes (characiforms, cichliforms, and siluriforms) after crude oil spilled in waterbody of the Amazon River basin. Credits to Barbara Fraser.

Negative impacts on fishes may substantially perturb food webs (Azevedo-Santos *et al*., 2016) and diminish environmental services (*e.g*., fish as food). For example, traditional human communities have reported that water bodies affected by crude oil experienced a notable decline in fish diversity (Sebastián, Hurtig, 2004), with subsequent but unstudied impacts on fishery production. As fishes disperse seeds (Correa *et al*., 2007; Reys *et al*., 2009), this is, for instance, another affected service. In fact, all consequences (*e.g*., input of metals, chlorides, cyanides, roads) of different mining activities reported here will affect food webs and ecosystem services.

Another common problem, especially in the Amazon basin, is oil extraction in headwater areas (Finer *et al*., 2008), implying that local spills can often extend downstream to other sites (Azevedo-Santos *et al*., 2016, 2019), pervasively affecting fish diversity and fisheries activities. This effect was recently observed in the Magdalena River in Colombia and in other Neotropical regions (Tab. 1).

After the input of massive amounts of a substance, especially in flowing waters, recovering the substance is difficult. In this case, petroleum, in addition to reaching downstream areas, remains present in aquatic organisms and sediment (*e.g*., Fig. 1); this persistence was verified after the oil spill resulting from the Deepwater Horizon accident (Liu, Liu, 2013). Therefore, freshwater fish from Amazonia and other Neotropical regions where leaks have occurred can be exposed to the negative effects of crude oil for months or years.

Input of metals. Different metals associated with mining operations can leach directly into watersheds; the volume and rate of the leaching are often unknown. Activities involved in the extraction of crude oil, gold, iron, and copper cause input of minerals into waterbodies. Some minerals have contaminated or otherwise affected Neotropical freshwater fishes (Tab. 2) – including in Amazonian systems, where small-scale mining activities, many of them illegal, are widespread. The sources of minerals in freshwater ecosystems are well known and include the failure of tailings disposal facilities and the chronic release of minerals during mining operations.

Many mines have tailings disposal facilities (hereafter TDFs; see fig. 1 in Salvador *et al*., 2020) that are used when large volumes of metal ores are mined (Tab. 3). The tailings may include finely ground rock (silt, powder), metals (*e.g*., cadmium), and processing chemicals and slimes, some of which are toxic (*e.g*., cyanides). These facilities are vulnerable to various disruptions (Nazareno, Vitule, 2016). When they collapse, TDFs release huge masses of toxic tailings, silt, and very turbid water into downstream environments (*e.g*., streams, rivers, floodplains, estuaries), causing extensive environmental changes. Numerous collapses of TDFs are reported in Neotropical countries (*e.g*., Wise, 2020), some of which have been highly publicized in popular media – especially when people died. However, for many of these cases little is known about the true magnitude of the impact of the accident on fishes, especially for events occurring before the 1990s.

In Brazil, TDF failures have resulted in catastrophic biodiversity losses in important rivers. The best-known examples, because of their social impacts and biodiversity losses, were the ruptures of the Fundão and Brumadinho TDFs, both in the State of Minas Gerais (Lambertz, Dergam, 2015; Fernandes *et al*., 2016; Cionek *et al*., 2019). In the case of Fundão, the refuse flowed downstream in the Doce River, in the southeastern part of Brazil (Carmo *et al*., 2017). This single event may have killed endemic, threatened, and undescribed fish species (Fernandes *et al*., 2016). The Brumadinho TDF rupture affected another major waterbody, the Paraopeba River, in the São Francisco River basin (Cionek *et al*., 2019), killing a huge number of fish. These events immediately changed limnological conditions and imported high levels of toxic mud (*i.e*., metals were present; Fernandes *et al*., 2016), impacting fishes. For example, the fish *Danio rerio* (Hamilton, 1822), exposed to the water from an affected waterbody (*i.e*., Paraopeba River), manifested high percentages of dead embryos or specimens with abnormalities (Thompson *et al*., 2020). In both cases, metals but also mud and other compounds in the TDF may have played a central role in the massive fish kill (Fernandes *et al*., 2016; Vergilio *et al*., 2020). Despite these catastrophes, Brazil currently has > 500 TDFs (Nazareno, Vitule, 2016), which may substantially damage ecosystems and fish diversity if – or when – they fail.

Metal inputs into Neotropical freshwaters also occur via other routes, including the deliberate or accidental release of effluents into waterbodies. Many rivers of different nations (*e.g*., Bolivia, Ecuador, French Guiana, Peru) probably received mercury during gold mining (Tab. 2), including many watercourses in the Amazon basin. Most contamination is likely related to illegal mining, a frequent activity in many

TABLE 2 | Neotropical freshwater fishes affected by metals in regions with records of mining activities (Methods in **S2**).

Mining	Pollutant	Waterbody	Country	References
Copper	Various metals	João Dias Stream	Brazil	Abril *et al.* (2018a,b)
Gold	Mercury	Tributaries of the Amazon basin	Brazil	Akagi *et al.* (1995)
Gold	Mercury	Magdalena River	Colombia	Alvarez *et al.* (2012)
Gold	Mercury	Piracicaba River	Brazil	Arantes *et al.* (2009)
Gold	Mercury	Paraíba do Sul River	Brazil	Azevedo *et al.* (2017)
Gold	Mercury	Madeira River	Brazil	Bastos *et al.* (2006, 2015); Bataglioli *et al.* (2019)
Gold	Mercury	Tartarugalzinho River basin	Brazil	Bidone *et al.* (1997a)
Gold	Mercury	Tapajós River	Brazil	Bidone *et al.* (1997b)
Gold	Mercury	Sinnamary River basin	French Guiana	Boudou *et al.* (2005)
Gold	Mercury	Tapajós River basin	Brazil	Brabo *et al.* (2000)
Gold	Mercury	Madeira River	Brazil	Dórea *et al.* (1998); Braga *et al.* (2015)
Gold	Mercury	Tapajós River basin	Brazil	Castilhos *et al.* (1998); Faial *et al.* (2015)
Gold	Mercury	Petit-Saut reservoir (Sinnamary River basin)	French Guiana	Durrieu *et al.* (2005)
Gold	Mercury	Madre de Dios River basin	Peru	Feingold *et al.* (2020)
Gold	Mercury	Paraguay River	Brazil	Ferreira *et al.* (2017)
Gold	Mercury	Upper Maroni River	French Guiana	Fréry *et al.* (2001)
Gold	Mercury	Lake Titicaca	Peru	Gammons *et al.* (2006)
Gold	Mercury	Several waterbodies	French Guiana	Gentès *et al.* (2019)
Gold	Mercury	Teles Pires River and Cristalino River	Brazil	Hacon *et al.* (2000)
Gold	Mercury	Paraguay River basin	Brazil	Hylander *et al.* (2000)
Gold	Mercury	Rivers of Amazon basin	Brazil	Kehrig, Malm (1999)
Gold	Mercury	Paraguay River basin	Brazil	Leady, Gottgens (2001)
Gold	Mercury	Piriá River and Grande Lake	Brazil	Lima *et al.* (2005)
Gold	Various metals	Cassiporé River basin	Brazil	Lima *et al.* (2015)
Gold	Mercury	Tapajós River basin	Brazil	Malm *et al.* (1995); Lino *et al.* (2019)
Gold	Mercury	Several tributaries of Amazon basin	Brazil	Malm (1998)
Gold	Mercury	Cauca and San Jorge River basins	Colombia	Marrugo-Negrete *et al.* (2018)
Gold	Mercury	Malinowski River	Peru	Martinez *et al.* (2018)
Gold	Mercury	French Guiana rivers	French Guiana	Maury-Brachet *et al.* (2020)
Gold	Mercury	Lake Managua	Nicaragua	McCrary *et al.* (2006)
Gold	Mercury	Coastal rivers	Suriname	Mol *et al.* (2001)
Gold	Mercury	Rivers of Cuyuní River basin	Venezuela	Nico, Taphorn (1994)
Gold	Mercury	Magdalena River	Colombia	Olivero, Solano (1998)
Gold	Mercury	Atrato River	Colombia	Palacios-Torres *et al.* (2018)
Gold	Various metals	Atrato River	Colombia	Palacios-Torres *et al.* (2020)
Gold	Mercury	Coastal rivers	Brazil	Palheta, Taylor (1995)
Gold	Mercury	Madeira and Paraíba do Sul River basins	Brazil	Pfeiffer *et al.* (1989); Pfeiffer *et al.* (1991)
Gold	Mercury	Tucuruí Reservoir and Moju River	Brazil	Porvari (1995)
Gold	Mercury	Iténez River	Bolivia	Pouilly *et al.* (2012, 2013)
Gold	Mercury	Mutum-Paraná and Madeira Rivers	Brazil	Reuther (1994)
Gold	Mercury	Tapajós River	Brazil	Santos *et al.* (2000, 2002)
Gold	Mercury	Solimões River basin	Brazil	Silva, Lima (2020)
Gold	Mercury	Solimões River	Brazil	Silva *et al.* (2019)
Gold	Mercury	Madeira River	Brazil	Soares *et al.* (2018)
Gold	Mercury	Bacajá River	Brazil	Souza-Araujo *et al.* (2016)
Gold	Mercury	Puyango River basin	Ecuador	Tarras-Wahlberg *et al.* (2001)
Gold	Mercury	Tapajós River basin	Brazil	Uryu *et al.* (2001)
Iron	Various metals	Doce River	Brazil	Fernandes *et al.* (2016); Ferreira *et al.* (2020); Macêdo *et al.* (2020); Weber *et al.* (2020)
Iron	Various metals	Paraopeba River	Brazil	Thompson *et al.* (2020); Vergilio *et al.* (2020)

Neotropical nations. These actions have led to extensive contamination, with likely lethal and sub-lethal effects on organisms. For instance, considerable research points to mercury in fish and in the environment of many Amazon rivers (Tab. 2). Mercury can cause genetic modification (Porto *et al*., 2005), brain disorders (Peterson *et al.,* 2007), and other toxic effects (Monteiro *et al*., 2017). Furthermore, because it is a toxic metal with bioaccumulation potential (Morel *et al*., 1998), mercury usually accumulates and, through the trophic transfer, may harm entire food webs, from smaller fish to top predators (*e.g*., *Salminus* spp., *Hoplias* spp., *Cichla* spp., *Caiman crocodilus*), including large mammals (*e.g*., *Trichechus inunguis*) and humans (Malm, 1998).

Another source of metal pollution, especially in the Amazon basin, is through oil extraction. In general, petroleum extraction involves the presence of water contaminated by heavy metals (Baqué, Doyle, 2017). Known as "produced water", this refuse has been released directly into waterbodies (Ibáñez, 1997; see also next subsection), as has been recorded in rivers from Colombia (Avellaneda, 1990), Ecuador (Ibáñez, 1997), and Peru (Baqué, Doyle, 2017). It is likely that the same input occurs in other Neotropical countries with high oil extraction activity (*e.g*., Venezuela). According to León, Zúñiga (2020:39), in only two areas of oil production in the Amazon, "approximately 408 million barrels" were generated in a single year and likely reached nearby waterbodies. The impacts of this waste on fish are unclear, as they have not been adequately examined. It is known that in regions where this waste was released, fish assemblages were contaminated by "copper, lead, zinc and mercury" (Baqué, Doyle, 2017:61). Other reports indicate that aquatic life was devastated in the presence of this waste (Ibáñez, 1997). It is likely that part of these effects is related to the presence of metals in the water, but other substances (*e.g*., chloride) may also be involved.

As with spills of crude oil and other substances, the release of metals, especially in high quantities, permeates entire river systems and affects fishes in adjacent environments and downstream habitats. This process was well documented in the failure of the Mariana TDF, which first contaminated a small watercourse, then spread through the mainstem of the Doce River (Fernandes *et al*., 2016; Carmo *et al*., 2017) and reached estuarine and marine ecosystems (Andrades *et al*., 2020). In fact, the problem of propagation of disturbances from headwater to downstream pervades all consequences of mining activities, including input of chemicals, deforestation, erosion and siltation, and roads, because these disturbances may occur in the upper sections of the watershed.

TABLE 3 | Major tailings disposal facilities (TDFs) that collapsed – with reports of effects on Neotropical freshwater fishes (Methods in **S3**).

Mining	Decade of collapse	River affected (country)	References
Lead and zinc	1990	Pilcomayo River (Bolivia)	Garcia-Guinea, Harffy (1998)
Gold	1990	Omai River (Guyana)	Vick (1996)
Bauxite	2000	Murucupi River (Brazil)	Silva *et al*. (2012)
Iron	2010	Doce River (Brazil)	Fernandes *et al*. (2016)
Iron	2010	Paraopeba River (Brazil)	Cionek *et al*. (2019); Thompson *et al*. (2020); Vergilio *et al*. (2020)

Input of cyanides. Gold mining activities in different Neotropical countries, for example, Argentina, Costa Rica, French Guiana, Guatemala, Mexico, Nicaragua, Panama, and Suriname, have been reported to use cyanide. In the Neotropical region, cyanide is used in both legal and/or illegal mining activities. For instance, in Minas Gerais (Brazil), the Mina do Engenho had dams with cyanide (**S4**). An example of the illegal use is the case of Costa Rica, in Central America. In this country, in 2019, an enforcement operation seized more than two tons of the product in an illegal mining area (**S5**).

When this pollutant reaches a water body – owing to the rupture of dams, rain, deliberate disposal, or other reasons – freshwater fishes are affected (Tab. 4). The main problem is that effluents containing the substance often end up in waterbodies (Caheté, 1998) – despite few scientific reports documenting occurrences. For example, a tributary of the Jáchal River basin in Argentina was contaminated by cyanide after a spill, but the effects on fish are still unclear. Other examples occurred in Mexico, where high cyanide concentrations reached the Piaxtla River and killed several immature fish (Tab. 4), and Honduras, where successive accidents introduced cyanide into the Lara River; in the latter case, there was a strong negative impact on the ichthyofauna (Tab. 4). These kills may occur for different reasons, including difficulty in breathing owing to the presence of the substance (Eisler, 1991).

Cyanides may affect fishes in different ways. As argued by Eisler (1991:27), "(...) adverse effects of cyanide on fish include delayed mortality, pathology, impaired swimming ability and relative performance, susceptibility to predation, disrupted respiration, osmoregulatory disturbances, and altered growth patterns". These problems may also have afflicted assemblages of the recorded disasters (Tab. 4). Immature forms may suffer the effects of these substances. For example, Leduc (1978) exposed *Salmo salar* Linnaeus, 1758, to hydrogen cyanide (HCN), a compound that may be also present in the mining. This author observed external changes in egg color and delayed hatching. For larvae, Leduc (1978) observed that the exposure to hydrogen cyanide resulted in morphological changes. This suggests that, in environments affected by cyanide, the recruitment of fish populations was also severely affected. In addition, the impact may propagate along the food chain, because cyanides also affect plants and macroinvertebrates (Eisler, 1991). Thus, the trophic structure of the entire community may be affected.

Input of chlorides, salts, polycyclic aromatic hydrocarbons (PAH). Produced waters extracted during oil extraction – in addition to metals (see subsection "Input of metals") – also contain other substances (Neff *et al*., 2011; Baqué, Doyle, 2017; Yusta-García *et al*., 2017). As mentioned, produced waters were dumped into many tributaries in the Amazon basin; for instance, the Corrientes, Pucacungayacu, Manchari, and Tigre Rivers (Yusta-García *et al*., 2017; see figures in Baqué, Doyle, 2017:59 and 61). There are reports of losses of Neotropical fish diversity from produced water (Ibáñez, 1997). Chloride, high levels of salts, and polycyclic aromatic hydrocarbons (PAH) (Neff *et al*., 2011) may play a role in the negative impacts on freshwater organisms. One impact may be due to the "chlorinity" effect in areas where produced waters are dumped (Kimerling, 2006:453). Ibáñez (1997) and Kimerling (2006) argued that this phenomenon may chemically block ecosystems and affect the routes used by the ichthyofauna during migration and spawning events. However, we emphasize that these effects (barriers) should be better evaluated.

The saline compounds, according to Neff *et al*. (2011), probably include sodium chloride (NaCl). Hintz, Relyea (2017) exposed rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792) to this substance. Among their results, the authors showed that, depending on the concentrations of sodium chloride, individual growth was negatively affected. Similarly, PAH is expected to be highly damaging to freshwater fishes in both the short and long terms (see subsection "Input of crude oil").

Erosion and siltation. Mining activities (iron, bauxite, gold, and copper) cause erosion and/or siltation in nearby waterbodies (*e.g*., Lin, Caramaschi, 2005; Nascimento *et al*., 2012; Verbete, 2012; Wantzen, Mol, 2013; Lobo *et al*., 2016; Melo *et al*., 2018), and in some cases the sediment may be contaminated by metals and other pollutants (Lopes *et al*., 2019). The extraction of other ores, like crude oil, may play a role in erosion and siltation (especially through deforestation and roads). These processes can have direct or indirect negative effects on fish. Erosion and siltation affect fish physiology, such as gill functioning (Wantzen, Mol, 2013). Other impacts include reduced water quality, loss of environmental heterogeneity, and altered habitats for fish feeding, refuge, reproduction, and development (Mol, Ouboter, 2004; Wantzen, Mol, 2013), especially through impacts on substrate interstices, leaf pack sedimentation, and aquatic plants. In a study evaluating the effects of erosion from a gold mine in Suriname, Mol, Ouboter (2004) showed that mining increased water turbidity with eroded material released from the mine. In addition, they reported "low habitat diversity, and a fish community with reduced diversity, few young fishes, and many fishes adapted to low light" (Mol, Ouboter, 2004:210). Erosion also contributes to the entry of mercury present in soil into the aquatic ecosystem, causing fish contamination (Richard *et al*., 2000). Another important case of siltation occurred in a lake in the Brazilian Amazon. Bauxite mining effluents, which include clay, were deposited for a decade in Lake Batata, in the Trombetas River basin (Bozelli, 1994; Lin, Caramaschi, 2005), and likely caused effects on fish diversity (Lin, Caramaschi, 2005).

In general, additional research is needed to better elucidate the negative impacts of siltation resulting from different mining activities on Neotropical fishes. However, silting from other human activities (Tab. 5) may serve as a baseline to predict the impacts of silting from mining. Inputs of sediments into aquatic environments resulting from anthropogenic actions have been incorporated into species extinction risk assessments (ICMBio, 2018). For example, silting is among the negative impacts listed to justify the classification of *Brycon vermelha* Lima & Castro, 2000, an endemic Brazilian fish, as endangered on the Brazilian red list (Santos *et al*., 2018). We emphasize that sediments from mining may carry metals (Lopes *et al*., 2019), which further increases the likelihood of adverse effects on freshwater fishes.

Deforestation. Mining activities (crude oil, gold, iron, copper, and bauxite) are also responsible for expanding deforestation (Kimerling, 2006; Swenson *et al*., 2011; Sonter *et al*., 2017; Espejo *et al*., 2018; Melo *et al*., 2018; Dethier *et al*., 2019; Diringer *et al*., 2020), directly or indirectly. For example, after a global crisis in the 2000s that affected several economies, the value of gold increased and, consequently, deforestation increased also in several Neotropical countries (Alvarez-Berríos, Aide, 2015) – indicating a strong correlation between mining and removal of vegetation.

TABLE 4 | Reports of cyanide spills due to mining in Neotropical region – including those with negative impacts on fish diversity (based on Methods and Search results in **S6A** and **S6B**, respectively).

Waterbodies	Country	Year of spill	Amount (liters)	Negative impacts on fish diversity
Bambana River	Nicaragua	1978	Unknown	Possibly
Omai and Essequibo Rivers	Guyana	1995	~1,230,258,830 to ~3,000,000,000	Yes
Several waterbodies	Panama	1998	Unknown	Possibly
Lara River	Honduras	2003	Unknown	Yes
Lara River	Honduras	2009	~568	Yes
San Sebastián River	El Salvador	Unknown	Unknown	Possibly
Puyango-Tumbes River	Ecuador	Unknown	Unknown	Possibly
Tributary of Velhas River	Brazil	2011	Unknown	Yes
Several waterbodies	Argentina	2015	1,000,000	Possibly
Piaxtla River	Mexico	2018	200	Yes
Tapajós River	Brazil	2018	Unknown	Possibly

TABLE 5 | Examples of negative effects of siltation on Neotropical freshwater fishes (Methods in **S7**).

Siltation reason	Disturbance	Country	References
Pasture	Decrease of the integrity of fish assemblages	Brazil	Casatti (2004)
Agriculture	Affect negatively the functional diversity	Brazil	Dala-Corte *et al.* (2016)
Mining	Decrease in fish diversity	Brazil	Lin, Caramaschi (2005)
Mining	Reduction of fish diversity	Suriname	Mol, Ouboter (2004)

The negative impact of deforestation from other activities (*e.g.*, conversion to pasture) on fish diversity is known (Tab. 6). However, negative effects of deforestation arising from mining require more research in Neotropical regions. In general, deforestation of riparian vegetation has resulted in strong changes in the ichthyofauna (*e.g.*, Tab. 6). The negative effects include, for instance, changes in taxonomic and functional features (Casatti *et al*., 2012) and losses of species, especially those sensitive to impacts (Dala-Corte *et al*., 2016). These same effects – or perhaps worse, because of contamination by metals – may occur on fishes in areas deforested owing to mining activities.

Roads. Virtually all types of mining (including crude oil, gold, iron, copper, and bauxite) need roads to transport the extracted ores or inputs (*e.g.*, cyanide). Therefore, the maintenance, rehabilitation, and construction of new roads are common processes in mining areas (Kimerling, 2006; Edwards *et al*., 2014). Construction of new roads is especially common in remote regions. For example, Texaco, the oil company, constructed long roads (> 600 km) in the Amazonian forest (Kimerling, 2006). New roads precipitate a sequence of disturbances from deforestation (*e.g.*, Barber *et al*., 2014) to erosion process and silting (Kimerling, 2006), besides introducing barriers to fish dispersal in small waterbodies (Leitão *et al*., 2018). The reasons for road construction are varied (Edwards *et al*., 2014), but their impacts are similar. The most important aspect is that roads fuel mining and other activities, including illegal ones.

New roads cause direct deforestation and open opportunities for ancillary activities, such as logging, construction of settlements, and other types of occupation (Barber *et al*., 2014). In addition, they cause direct and indirect erosion (Smith *et al*., 2018). New roads also fragment aquatic habitats, and many studies (*e.g*., Belford, Gould, 1989; Mariano *et al*., 2012; Brejão *et al*., 2020) have demonstrated that road culverts hinder hinder the movement of fishes. For example, Makrakis *et al.* (2012) evaluated the negative impacts of culverts, showing that 90% of them seriously threat fish movements. Brejão *et al.* (2020), studying Amazonian streams, found that roads crossing these small waterbodies affected the distribution of ichthyofauna by fragmenting habitats. A case of roads constructed for mining that generated negative impacts on fishes was reported for the Amazon. Kimerling (2001:330) described how the company Occidental Petroleum constructed a road in the El Eden region, in Ecuador, that "blocked the migration of fish from a lake into seasonally flooded forest".

Roads also directly or indirectly pollute aquatic ecosystems. For example, exploration for crude oil in Ecuadorian Amazonia resulted in roads coated with oil that, in turn, polluted several waterbodies with high fish diversity (Kimerling, 2006). Run-off may have generated several negative effects, lethal and non-lethal, on fishes (see subsection "Input of crude oil"). Another type of pollution may come from the usage of these roads for mining. An event that received prominence was the contamination of the Yaqui River, in Mexico (near the Neotropical limits), with cyanide (**S9**). The pollution occurred after an accident with a truck transporting the substance to a mine (**S9**). Cases like these are likely to occur frequently in the Neotropical region, but they are not reported to authorities and do not receive the attention of the media. Other types of pollution arising from roads are eutrophication processes (Smith *et al*., 2018), plastics (Windsor *et al*., 2019), and solid and liquid waste from traffic. These disturbances harm the aquatic biota.

A GROWING THREAT

Currently, political forces work to expand mining activities across Neotropical countries. In Brazil, particularly, plans are afoot to expand the activity across the country, especially in the Amazon, Southeast, and Northeast regions (Ferreira *et al*., 2014; Villén-Perez *et al*., 2017). The strong lobby of the mining sector has spurred revisions in Mining Code legislation (Meira-Neto, Neri, 2017). A direct result of this movement has been the creation of the National Mining Agency in 2017, which has increased the sector's autonomy and political power against environmental restrictions. Moreover, the Brazilian Congress is currently analyzing bills that propose mining in protected areas and indigenous lands, in addition to a constitutional amendment that proposes simplifying the environmental licensing system (El Bizri *et al*., 2016; Villén-Perez *et al*., 2017; Congresso Nacional, 2020). Such simplification, if approved, will enable the construction/operation of large-scale projects, including mining, without the need for rigorous environmental assessments (Fearnside, 2016). The mining lobby strengthened after the election of President Jair Bolsonaro, who has defended a "development" agenda with little regard for the environment and sustainability (Azevedo-Santos *et al*., 2021; Thomaz *et al*., 2020; Pelicice, Castello,

2021) and with political and legal incentives for the agrarian and mining sectors (Campo-Silva, Peres, 2019). The president himself has expressed his desire to allow the exploration for mineral resources in protected areas and indigenous lands of the Amazon. Rather than these current activities, Brazil should play an important role in avoiding policies that erode the Neotropical ichthyofauna. This is because, based on recent publications on described species (ICMBio, 2018; Albert *et al*., 2020), we estimate that the country holds a little more than 50% of species richness of freshwater fishes of the Neotropics. Using other sources of information (ICMBio, 2018; Fricke, Eschmeyer, 2021), we suggest that Brazil harbors between 16 to 18% of the species richness of freshwater fishes of the planet. This is an extraordinarily high diversity for a single jurisdiction. This outsize role suggests that political action, for example, at the federal level to expand mining at any cost, can affect a considerable portion of the Neotropical freshwater fishes.

The trend of expanded mining activity has been observed in many other countries of the Neotropical region (Hammond *et al*., 2013) and will complicate the current scenario. Small-scale mining is widespread in Neotropical nations (Harlow *et al*., 2019), and many mines are located within protected areas (Kamino *et al*., 2020). In addition, illegal activities are frequent in remote regions, for example, in parts of Amazonia. Currently, inspection and monitoring of mining activities have been insufficient, while fines and sanctions for environmental damage have rarely been paid (especially in large-scale catastrophes), and emergency, management, and environmental restoration plans have been negligent, precarious, or absent (Cionek *et al*., 2019; Salvador *et al*., 2020). Further weakening legislation will reduce environmental restrictions and fuel the expansion of the activity, including in protected areas, where more than 10,000 projects await authorization (Villén-Perez *et al*., 2017). One important concern is the

TABLE 6 | Examples of negative impacts of deforestation on Neotropical freshwater fishes (Methods in **S8**).

Deforestation type	Disturbance	Country	References
Agriculture and pasture	Changes in density	Ecuador	Bojsen, Barriga (2002)
Pasture	"Negative threshold responses"	Brazil	Brejão *et al.* (2018)
Pasture and agriculture	Alterations in both taxonomic and functional features	Brazil	Casatti *et al.* (2012)
Pasture	Changes in species composition	Brazil	Costa *et al.* (2020)
Pasture and agriculture	Alterations in the size of fishes	Brazil	Ilha *et al.* (2018)
Agriculture	Increase of abundance of some species	Brazil	Ilha *et al.* (2019)
Agriculture	Change in functional composition	Brazil	Leitão *et al.* (2018)
Pasture and grassland	“Functional changes”	Brazil	Lobón-Cerviá *et al.* (2016)
Pasture	Changes in abundance	Costa Rica	Lorion, Kennedy (2009)
Pasture	Change in functional groups	Brazil	Teresa *et al.* (2015)
Pasture	Changes in richness and abundance	Brazil	Virgilio *et al.* (2018)

political influence of the mining sector, because mining companies have traditionally financed political campaigns, which has fueled corruption (Meira-Neto, Neri, 2017).

As mining activities – together with hydroelectric power plans (Winemiller *et al*., 2016) and other human actions (Pelicice *et al*., 2017, 2021; Tófoli *et al*., 2017; Daga *et al*., 2020; Mezzaroba *et al*., 2021) – expand in different nations, impacts on Neotropical biodiversity will become increasingly prominent. The maintenance of freshwater fish diversity in the region will depend on policies that regulate mining activities so that their expansion is balanced with the protection of ecosystems and biodiversity.

CONCLUSION

The diversity of Neotropical fishes, together with their ecosystem services, have been affected in different ways by mining activities. The main negative impacts come from input of crude oil, contamination by metals and other pollutants, erosion, silting, deforestation, and road construction. Some consequences, especially crude oil spills and the rupture of tailing dams, have brutal and long-lasting negative impacts on aquatic ecosystems. Although impacts are undisputable, there is a clear need for more scientific research. The present review demonstrated that the number of studies is still relatively small, and some impacts remain largely uninvestigated. The unpredictable nature of accidents, in particular, makes it difficult to plan studies, indicating the need for continuous and long-term monitoring of the fish fauna, especially in large or risky mining operations. Experimental and field studies are needed to fill important gaps concerning the response of fish to different consequences of mining activities.

The fact that mining activities damage the fish fauna should guide Neotropical countries to review their mining plans to establish more rigorous regulations and to adopt measures to contain illegal developments. We emphasize that some activities cause acute impacts in particular conditions (*i.e*., TDS spills), whereas others affect the environment continuously (*e.g*., gold mining), making it difficult to mitigate their effects. This fact increases the need for advances in inspection and monitoring programs, especially in areas where impacts have been reported and where they are likely to occur.

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AUTHORS' CONTRIBUTION

Valter M. Azevedo-Santos: Conceptualization, Formal analysis, Methodology, Supervision, Writing-original draft, Writing-review and editing.

Marlene S. Arcifa: Methodology, Writing-original draft, Writing-review and editing.

Marcelo F. G. Brito: Methodology, Writing-review and editing.

Angelo A. Agostinho: Writing-review and editing.

Robert M. Hughes: Writing-review and editing.

Jean R.S. Vitule: Writing-review and editing.

Daniel Simberloff: Writing-review and editing.

Julian D. Olden: Writing-review and editing.

Fernando M. Pelicice: Writing-review and editing.

ETHICAL STATEMENT

Not applicable.

COMPETING INTERESTS

The authors declare no competing interests.

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SUPPLEMENTARY MATERIAL S1

A. METHODS

Searches were conducted between September 2020 and March 2021 using the Google website as a base (https://www.google.com). For the searches withing the Google base, we used the words "oil spill + amazon + fish kill", "oil spill + Amazon + fish dead", "oil leak + Peru", "oil leak + Colombia", "oil spill + Amazon river", "oil spill + Brazil", "pipeline + fish kill", "Iguacu River + oil pill". In addition, we combined the name of oil and/or gas producing countries in Neotropical region (*i.e*., Argentina, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Cuba, Ecuador, Guatemala, Mexico, Peru, Surinam, Trinidad and Tobago, Venezuela) with the key words "oil spills" + "river" or "lake" or "stream" (*e.g*., peru + oil spill + river). Searches were performed using these combinations of words in Portuguese, English, and Spanish; and were conducted exhaustively only for negative impacts of input of crude oil on Neotropical freshwater fishes. In each search, we considered only the first 20 pages of results. We considered oil spills in gas and oil blocks, oil fields, tank farm, or from pipelines.

B. SEARCH RESULTS

Andean River to Lake Titicaca (2000):

https://apnews.com/article/df10614adc20601990008831f10f08c3

https://ejatlas.org/print/desaguadero-oil-spill-transredes-s-a-bolivia

Stream to the Barigui and after to the Iguaçu River (2000):

http://news.bbc.co.uk/2/hi/americas/840379.stm

https://www.theguardian.com/environment/2000/jul/19/oilspills.internationalnews

Catatumbo River to Lake Maracaibo (2001):

https://neftegaz.ru/en/news/crime/435570-venezuela-fights-to-halt-river-borne-oil-slick

Coatzacoalcos River (2004):

https://noticias.ambientebrasil.com.br/clipping/2004/12/24/17439-vazamento-de-petroleo-atinge-praias-do-golfo-do-mexico.html

https://www.latimes.com/archives/la-xpm-2005-jan-16-fg-mexspill16-story.html

Coatzacoalcos River (2011):

https://expansion.mx/planetacnn/2012/01/14/limpiar-por-completo-el-derrame-de-crudo-en-veracruz-tomara-un-mes-mas

Catatumbo River to Lake Maracaibo (2012):

http://www.ipsnews.net/2012/04/ecobreves-venezuela-oil-spill-halts-fishing-in-lake-maracaibo

Guarapiche River (2012):

Carvajal AC, Oletta JF. Derrames petroleros y sus efectos sobre la ecología y la salud humana. Noticia Epidemiológica. 2012; 1 (35):1–40.

Coca River (Amazon basin) (2013):

https://www.bbc.com/news/world-latin-america-22836975

Lake - Unknown name (2014):

https://news.mongabay.com/2016/09/negotiations-and-protests-ongoing-in-wake-of-oil-spills-in-peruvian-amazon

A tributary of the Marañón River basin (2014):

https://news.mongabay.com/2015/03/9-months-after-amazonian-oil-pipeline-spill-effects-and-fears-linger

Stream - Unknown name (2014):

Fraser B. Oil in the forest. Science. 2016; 353(6300): 641–43.

Stream - Unknown name (2015):

https://agenciabrasil.ebc.com.br/geral/noticia/2015-06/vazamento-em-oleoduto-da-transpetro-atinge-corrego-e-chega-ao-mar

Chiriaco and Morona Rivers - 1 (2016):

https://www.bbc.com/news/world-latin-america-35636738

Chiriaco and Morona Rivers - 2 (2016):

https://news.mongabay.com/2016/06/breaking-oil-spill-in-peruvian-amazon-puts-local-communities-at-risk

Stream - Unknown name (2016):

https://news.mongabay.com/2016/06/breaking-oil-spill-in-peruvian-amazon-puts-local-communities-at-risk

Tepeyac stream and Coatzacoalcos River (2018):

https://mexiconewsdaily.com/news/veracruz-oil-spill-300-evacuated

Streams, Sogamoso and Magdalena Rivers (2018):

https://www.nsctotal.com.br/noticias/emergencia-ambiental-na-colombia-por-vazamento-de-petroleo

https://thebogotapost.com/oil-spill-wreaks-havoc-in-santander/28756

Coca and Napo Rivers (2020):

https://earther.gizmodo.com/an-oil-spill-and-the-coronavirus-are-creating-a-crisis-1843338899

Godineau River (2020):

https://trinidadexpress.com/newsextra/oil-spills-into-the-godineau-river/article_9ce5ce3c-2a6f-11eb-8102-7f9a11803055.html

Shiripuno River (2020):

https://es.mongabay.com/2021/02/derrame-petroleo-rio-shiripuno-ecuador

SUPPLEMENTARY MATERIAL S2

METHODS

Searches were conducted between September 2020 and March 2021. Searches of articles published in scientific journals (*i.e.*, excluding gray literature) were conducted in five databases: Google Scholar (https://scholar.google.com.br), Orcid (https://orcid.org), ResearchGate (https://www.researchgate.net), Science Direct (https://www.sciencedirect.com), and Web of Science (www.webofknowledge.com). For searches, we combined the following words: "mining + fish"; "mining + fish + country of Neotropical region (*e.g.*, Suriname)"; "Amazon + mining + mercury + fish"; "mercury + Neotropical fish + effects on organs"; "Samarco + fish + Doce River"; "mining + Fundão + Samarco + Brumadinho + fish"; "Lake Batata + effects on fish", "ecotoxicological + mercury"; "toxicological + mercury". Searches were performed using these combinations of words in Portuguese, English, and Spanish; and were conducted exhaustively only for negative impacts (*e.g.*, contamination) on Neotropical freshwater fishes.

SUPPLEMENTARY MATERIAL S3

METHODS

Searches were conducted between September 2020 and March 2021. We searched for impacts on fish diversity on Google Scholar (https://scholar.google.com.br), including gray literature. We used as a starting point the name of each major collapsed dam that was listed in Wise (2020) combined with the following words: fish kill; fish mortality; ichthyofauna; fish fauna. In the same search base, we used the combination of the words: "mining rupture + fish"; "tailings dam + collapse". Searches were performed using these combinations of words in Portuguese, English, and Spanish; and were conducted exaustivatelly only for negative impacts on Neotropical freshwater fishes.

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SUPPLEMENTARY MATERIAL S4
ON THE CYANIDE AT MINA DO ENGENHO DAM.

In Portuguese:

https://g1.globo.com/mg/minas-gerais/noticia/2019/01/31/barragens-com-maior-potencial-de-dano-do-pais-oferecem-risco-de-contaminacao-quimica-a-manancial-na-grande-bh.ghtml

SUPPLEMENTARY MATERIAL S5
ILLEGAL MINING IN COSTA RICA.

In English: https://ticotimes.net/2019/12/10/costa-rica-seizes-cyanide-and-mercury-in-operations-against-illegal-mining

In Spanish: https://www.estrategiaynegocios.net/centroamericaymundo/1340855-330/costa-rica-decomisa-cianuro-y-mercurio-en-operativos-contra-miner%EDa-ilegal

SUPPLEMENTARY MATERIAL S6
A. METHODS

Searches were conducted between September 2020 and March 2021 using the Google website as a base (https://www.google.com) and Google Scholar (https://scholar.google.com.br). For the searches withing the Google base, we used the words "cyanides", "cyanide" combined with Neotropical countries (*e.g*., Nicaragua, Brazil), "fish", or "river", or "freshwater", or "mining", or "gold", or "spill". Searches were performed using these combinations of words in Portuguese, English, and Spanish; and were performed exhaustively only for negative impacts of cyanide on Neotropical freshwater fishes. In each search, we considered only the first 20 pages of results.

B. SEARCH RESULTS

Bambana River (1978):

Tolvanen A. The Legacy of Greenstone Resources in Nicaragua. 2003.

Omai and Essequibo Rivers (1995):

http://www.earthtimes.org/pollution/guyana-suspends-gold-diamond-mining-permits/2075

Hilson G, Monhemius AJ. Alternatives to cyanide in the gold mining industry: what prospects for the future? Journal of Cleaner Production 2006; 14:1158–67.

https://www.independent.co.uk/news/world/cyanide-from-mine-threatens-guyana-river-1597531.html

https://www.spokesman.com/stories/1995/aug/23/cyanide-poisons-major-guyana-river-325-million

Several waterbodies (1998):

http://www.ipsnoticias.net/1998/06/panama-clamor-contra-mineria-sucia-por-grave-derrame-de-cianuro

Lara River (2003):

https://wp.radioprogresohn.net/una-mina-de-sangre-y-oro-que-destruye-cerros-en-la-union-copan

Lara River (2009):

https://www.laprensa.hn/honduras/515888-97/honduras-fuga-de-cianuro-cae-al-rio-lara

https://www.biodiversidadla.org/Noticias/Honduras_nuevo_derrame_de_cianuro_al_rio_por_Yamana_Gold

San Sebastián River (Unknown):

https://noalamina.org/latinoamerica/guatemala/item/9368-confirman-hierro-y-cianuro-en-rio-san-sebastian

https://pueblosencamino.org/?p=128

Puyango-Tumbes River (Unknown):

Marshall BG, Veiga MM, Silva HAM, Guimarães JRD. Cyanide contamination of the Puyango-Tumbes River caused by artisanal gold mining in Portovelo-Zaruma, Ecuador. Curr Environ Health Rep. 2020; 7:303–10.

Tributary of Velhas River (2011):

http://g1.globo.com/brasil/noticia/2011/09/em-mg-contaminacao-de-rio-podera-ser-investigada.html

https://veja.abril.com.br/brasil/em-mg-contaminacao-de-rio-podera-ser-investigada

Several waterbodies (2015):

https://archivo.gestion.pe/empresas/barrick-confirma-multa-us-93-millones-y-lamenta-derrame-cianuro-argentina-2156219

https://www.rumbominero.com/noticias/mineria/barrick-confirma-multa-de-9-3-millones-de-dolares-y-lamenta-derrame-de-cianuro-en-argentina

Piaxtla River (2018):

http://www.mining.com/mexican-environment-officials-visit-mine-following-cyanide-spill

https://www.telesurenglish.net/news/Cyanide-Spill-in-Mexico-Traced-Back-to-Canadian-Mining-Company-20180324-0016.html

https://www.unotv.com/noticias/estados/durango/detalle/contaminacion-rio-piaxtla-derrame-cianuro-099325

Tapajós River (2018):

https://g1.globo.com/pa/santarem-regiao/noticia/2018/09/27/laudo-da-pf-alerta-para-volume-absurdo-de-lama-despejada-na-bacia-do-rio-tapajos.ghtml

SUPPLEMENTARY MATERIAL S7

METHODS

Searches were conducted between September 2020 and March 2021. Searches of articles published in scientific journals (*i.e.*, excluding gray literature) were conducted in five databases: Google Scholar (https://scholar.google.com.br), Orcid (https://orcid.org), ResearchGate (https://www.researchgate.net), Science Direct (https://www.sciencedirect.com), and Web of Science (www.webofknowledge.com). For searches, we combined the following words: "siltation effects + mining, agriculture, Neotropical fish"; siltation impacts + Neotropical fish"; and "siltation + fish". We also verify reference list of articles found; and articles citing articles found. Searches were performed using these combinations of words in Portuguese, English, and Spanish; and were conducted exhaustively only for negative impacts of siltation from mining activities on Neotropical freshwater fishes. For other activities (*e.g.*, agriculture), the search was not exhaustive, and we choose just examples of works found.

SUPPLEMENTARY MATERIAL S8

METHODS

Searches were conducted between September 2020 and March 2021. Searches of articles published in scientific journals (*i.e.*, excluding gray literature) were conducted in five databases: Google Scholar (https://scholar.google.com.br), Orcid (https://orcid.org), ResearchGate (https://www.researchgate.net), Science Direct (https://www.sciencedirect.com), and Web of Science (www.webofknowledge.com). For searches, we combined the following words: "deforestation + Neotropical fish + erosion + agriculture + mining"; "deforestation in the Neotropical region + effects on fish"; "deforestation + fish"; "deforestation + fish + Neotropical". We also verify reference list of articles found; and articles citing articles found. Searches were performed using these combinations of words in Portuguese, English, and Spanish; and were conducted exhaustively only for negative impacts of deforestation from mining activities on Neotropical freshwater fishes. For other activities (*e.g.*, agriculture), the search was not exhaustive, and we choose just examples of works found.

SUPPLEMENTARY MATERIAL S9

TRUCK LEAK

In Spanish: https://www.jornada.com.mx/2013/08/28/estados/030n1est

In Spanish: https://www.eleconomista.com.mx/politica/Confirman-un-muerto-y-derrame-de-cianuro-tras-vuelco-en-Sonora-20130823-0081.html

In Spanish: https://www.excelsior.com.mx/nacional/2013/08/27/915616

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