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RESEARCH ARTICLE

Effect of reduced impact logging and small-scale mining disturbances on Neotropical stream fish assemblages

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Abstract Deforestation and mining are recognized as major threats to Amazonian biodiversity, but, in addition to the well known impacts of clear cutting and industrial mining, the impact of cryptic threats such as illegal small-scale gold-mining and reduced impact logging remain little known. Here, we quantify the impact of those cryptic disturbances on a set of 201 sites dispersed throughout French Guiana. The fish assemblages of 139 pristine forest sites were compared to 16 sites subjected to reduced impact logging (i.e. selective logging), 24 sites with ongoing small-scale gold-mining and 22 sites formerly mined for gold. Controlling for the environmental variability between sites showed the significant structuring effect of all disturbances on fish taxonomic structure, with a marked impact of gold-mining. This effect was of strong magnitude and remained significant after mining activity ceased. In contrast, the reduced impact logging effect remains of low magnitude, although significant. From a functional point of view, gold-mining drives species assemblages towards a decrease in the richness of small-sized stream habitat specialist species and favours larger ubiquitous species living in both streams and rivers. Reduced impact logging effect was slighter, and negatively affected only the richness of phytophagous species. These results, encompassing a variety of hydrographic basins, unambiguously show the detrimental effect of small-scale gold-mining on fish assemblages as well as the slight effect of reduced impact logging. Since gold-mining is one of the most widespread threats throughout the Amazonian region, particular care should be given to controlling this, often illegal, activity.

Keywords Amazon basin · Anthropogenic disturbances · Deforestation · Functional diversity · Freshwater · Guiana shield · Taxonomic diversity

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Introduction

The Amazonian region, including Amazon basin and Guiana shield, represents the world's largest rainforest. It hosts an unequalled diversity of organisms, including both plants (Ter Steege et al. 2013) and animals (e.g. Grenyer et al. (2006) for terrestrial vertebrates and Oberdorff et al. (2011) for freshwater fishes). This region, like almost everywhere on Earth, is subject to anthropogenic disturbances, among which land use change is the most prominent (Sala et al. 2000). Logging and gold-mining are two major man-made disturbances that contribute to this land use change (Peterson and Heemskerk 2001; Millennium Ecosystem Assessment Program 2005). For instance, in Amazonia, the annual average loss of rainforest surface area associated with gold-mining tripled in 2008 (Asner et al. 2013), and 169,000 km^2 of forest were degraded by logging and deforestation in Brazil during the last decade (Souza Jr et al. 2013). Much attention has been given to these harsh disturbances, leading in 1986 to the establishment, under the auspices of the United Nations, of the International Tropical Timber Organization, which promotes political decisions on the control and *regulation* of deforestation. Those decisions led to the application, at least locally, of tropical forest sustainable management plans (Blaser et al. 2011), such as reduced impact logging (Dias et al. 2010). Similar measures were adopted for gold-mining to reduce the impact of legal mining and fight against illegal activities (Taubira 2011). Those restrictions were efficient in controlling industrial mining development, but did not stop the rise of illegal, small-scale mining activities, which are more cryptic than large, legal mines (Hammond et al. 2007). The influence of the reduced impact strategies on terrestrial plants and animals was reviewed by Peres et al. (2010), who showed that impacts are different between taxa. A minor impact was reported for ants, arachnids, birds and mammals (Azevedo-Ramos et al. 2006; Castro-Arellano et al. 2007; Bicknell and Peres 2010), while other taxa such as bats seem to be more sensitive to disturbances (Peters et al. 2006; Presley et al. 2007). Those studies were mainly focussed on terrestrial organisms, and the impact of reduced impact logging (i.e. selective logging) and small-scale mining on freshwater ecosystems remains little studied (but see Wantzen and Mol 2013), although aquatic ecosystems are known to be an integrator of man-made disturbances across hydrographic basins (Lake et al. 2000; Allan and Castillo 2007; Paukert et al. 2011; Li et al. 2012).

Mining and deforestation affect aquatic ecosystems in various ways. They increase sediment load and are hence responsible for rises in turbidity (Bruijnzeel 1990; Dall'Agnol 1995; Wantzen and Mol 2013) that affect species survival by causing abrasion, clogging gills, and smothering fish eggs, algae and benthic invertebrates (Alabaster and Lloyd 1980; Bruton 1985; Wood and Armitage 1997; Parkhill and Gulliver 2002; Tudesque et al. 2012). These disturbances also reduce canopy cover and hence increase luminosity and water temperature, but also reduce the input of litter and woody debris (Wright and Flecker 2004). Such environmental changes are known to affect the structure and the composition of fish communities (Bojsen and Barriga 2002; Wright and Flecker 2004).

It should however be noted that previous studies on the effects of mining and deforestation on fish assemblages were conducted in highly-disturbed sites (Wright and Flecker 2004; Yule et al. 2010), and only a few studies were devoted to lesser disturbances generated by reduced impact logging (e.g. Bojsen and Barriga 2002; Dias et al. 2010) or small-scale gold-mining (e.g. Mol and Ouboter 2004; Brosse et al. 2011; Wantzen and Mol 2013). All those studies detected a detrimental effect of man-made disturbances on fish assemblage composition, biomass and productivity. Those local results from various locations appeal for a wider spatial approach encompassing numerous sites over several river basins. Such a regional approach, although considering a higher environmental and faunistic heterogeneity that needs to be controlled using appropriate statistical analyses, allows testing for the generality of the local disturbance trends over the considered region.

We investigated the effects of reduced impact logging (also called selective logging) and small-scale gold-mining on small primary forest streams dispersed over the entire territory of French Guiana. We considered fish assemblages in 201 sites (139 pristine, 24 currently gold-mined, 22 formerly gold-mined and 16 subjected to reduced impact logging) dispersed throughout more than 60,000 km^2 and encompassing more than 10 drainage basins.

Our aim was first to test whether anthropogenic disturbances were sufficiently harsh to be detectable using overall descriptors of fish assemblages, such as species richness or abundance. We then quantified changes in the taxonomic and functional structure of fish assemblages induced by anthropogenic disturbances over the region considered, and finally analysed the magnitude of these impacts after controlling regional (basin membership), stream reach (site position in the river continuum) and local (habitat) effects.

Methods

Study area

This study was conducted in French Guiana. Almost the entire territory is covered by dense primary rainforest, and the ca 450 freshwater fish species are distributed over seven major basins. French Guiana therefore hosts typical Amazonian fauna (sensu lato, including the Guiana shield) (Boujard et al. 1997; De Merona et al. 2012). All the basins share the same core of species, although a marked species turnover between basins has been reported (Brosse et al. 2013). Such turnover reflects the biogeographic history of the basins (Boujard et al. 1997; De Merona et al. 2012). During the last quaternary glaciations, all but one basin dried up and only the Maroni on the west and the Amazon on the east acted as fish refuges. Post-glacial recolonisation was hence achieved from distinct river basins (i.e. the Amazon and Maroni, with Orinoco relatives) therefore explaining some taxonomic differences between river basins (De Merona et al. 2012).

Sampling sites

The sampling sites were distributed over the seven main river basins (Fig. 1), but the sampling effort was greater in

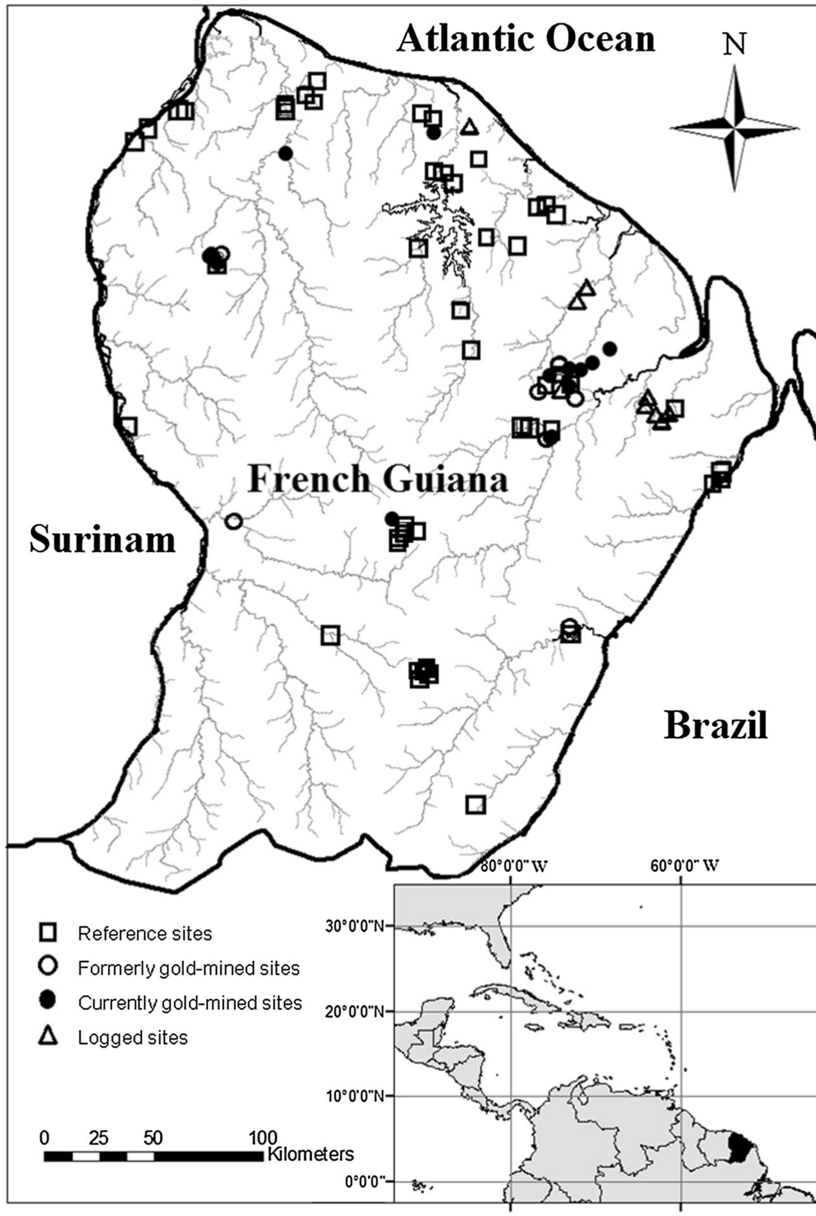

Fig. 1 Map of French Guiana showing site locations on the hydrographic network. *Symbols* represent anthropogenic disturbances, Logging refers to sites subjected to reduced impact logging

the northern part of French Guiana due to the remoteness of the southern part of the territory that limited our ability to sample more sites. We nevertheless collected southern samples from all of the main river basins (Fig. 1). All the sites are located on small perennial streams flowing in a primary forest environment. Streams flowing under secondary forest, savannas, temporary streams, as well as coastal streams influenced by the tide were not considered. The stream width of the sites sampled did not exceeded 10 m in all but one site, a shallow sandy channel of 13.6 m width (see Table 1). All the streams were less than 1 m deep, making the sampling sites comparable from an environmental point of view. Indeed, a previous study showed a continuum of environmental conditions but no clear typology within those Guianese streams (Dedieu et al. 2014).

The 201 sampling sites were categorized into four types corresponding to four levels of anthropogenic disturbance. Reference sites (n = 139) were defined as sites not subjected to anthropogenic impacts such as gold-mining, deforestation, chemical pollution, agricultural or urban runoff. All reference sites are located in forest areas that have been unexploited and uninhabited for at least one century. For all those sites, there were no human settlements or recorded impacts throughout the entire drainage basin upstream of the sampling site.

Reduced impact logging sites (n = 16) were subjected to selective logging, which is strictly defined and controlled

Table 1 Environmental characteristics of the reference, logged, formerly and currently gold-mined sites

	mean (±SD)	min.	max.
Reference sites			
Width (cm)	365.53 (±209.04)	97	1356
Wood (%)	13.52 (±12.23)	0	50
Litter (%)	25.50 (±23.60)	0	85
Coarse substr. (%)	15.94 (±25.42)	0	100
Logged sites			
Width (cm)	310.20 (±138.31)	193	758
Wood (%)	15.31 (±18.83)	0	60
Litter (%)	23.93 (±27.53)	0	95
Coarse substr. (%)	11.56 (±18.77)	0	50
Formerly gold-mined sites			
Width (cm)	427.77 (±197.35)	173	907
Wood (%)	13.86 (±17.10)	0	70
Litter (%)	11.81 (±13.67)	0	50
Coarse substr. (%)	27.95 (±29.42)	0	90
Currently gold-mined sites			
Width (cm)	407.64 (±180.87)	135	777
Wood (%)	8.54 (±8.27)	0	30
Litter (%)	16.25 (±23.55)	0	80
Coarse substr. (%)	31.04 (±33.42)	0	90

Mean (±SD), minimal and maximal values are given for each variable

by the Forest National Office (Panchout 2010). At those sites, 4.5 trees ha^{-1} are on average extracted, and forestry work is limited to the dry season to reduce erosion. For the same reason, timber cutting is not allowed within 100 m from a stream. All the logging sites are under activity, so logging impact is comparable for all the sites. It should be noticed that we did not consider more drastic logging impacts. Although clear cutting (slash-and-burn agriculture) occurs in French Guyana, it remains limited and mainly occurs in secondary forest areas.

The remaining sites were formerly subjected to gold-mining but are no longer exploited (n = 22), or are currently subjected to gold-mining (n = 24). Both formerly and currently gold-mined sites represent illegal, small-scale gold-mining activity. Those mining sites were exploited by a few workers without heavy equipment (the miners cross the forest on foot with all their equipment) and remain hidden under the canopy (Hinton et al. 2003). The intensity of mining is difficult to measure using aerial photographs because it does not generate extended deforestation (Alvarez-Berríos and Aides 2015). For the same reason, we cannot quantify the duration of the mining activity for both currently and formerly mined sites. The formerly mined sites had been abandoned for 6–12 months, but we are unable to provide an exact date for the cessation of activity due to the illegal nature of the mining.

In the disturbed sites (i.e. currently and formerly gold-mined, and logged sites), fish were sampled 100–500 m downstream from the disturbed site as, for reasons of security (particularly for the gold-mined sites), it was not possible to access the mining or logging area. At all disturbed sites, there was no stream confluence between the disturbed area and the sampling site.

Sampling methodology

Sampling occurred from 2008 to 2012 during the dry season (September-December), to ensure an optimal fishing efficiency (Mol and Ouboter 2004). At each site, a section of river was isolated using two fine mesh (4 mm) stop nets to keep fish from escaping from the sampling section. Each section encompassed a homogeneous hydromorphologic unit that has been assigned to one of the following groups: (i) shallow and fast-flowing (riffles); (ii) deep and slow-flowing (pools); and (iii) intermediate conditions (runs). The length of each section was proportional to stream width. Stream section length varied from 4 to 52.7 m and was on average 5.9 ± 3.7 times longer than stream width. Moreover, we avoided sampling pools deeper than 1 m and the zones obstructed by fallen trees where distinguishing fish is difficult. Fish were sampled by releasing a small quantity of rotenone (PREDATOX®: a 6.6 % emulsifiable solution of rotenone extracted from *Derris elliptica* by Saphyr, Antibes, France) a few meters upstream from the first net. This is the only efficient method for collecting all the fish species at all sites (Allard et al. 2014). Particular attention was paid to releasing as little toxicant as possible to avoid fish mortality downstream from the section studied. Moreover, study sections were located just upstream from a confluence to ensure the sufficient dilution of the rotenone downstream from the study section and hence avoid undue fish mortality. For a complete description of the rotenone sampling method, see Merigoux and Ponton (1998).

Fish species were then identified according to Planquette et al. (1996), Keith et al. (2000), Le Bail et al. (2000, 2012). Some specimens from each species were collected and fixed in a 5 % formaldehyde solution for taxonomic confirmation. All fish captured were identified and counted.

Three species traits were considered after consulting the literature. Trophic guilds were represented by three categories: phytophagous, omnivorous, and piscivorous. Body size was the maximal body size of the species (i.e. maximal standard length) as specified in Fishbase (www.fishbase.org). We also considered three major habitat preferences, according to the literature (Planquette et al. 1996; Keith et al. 2000; Le Bail et al. 2000): small stream specialists (i.e. species inhabiting only headwater streams; hereafter, Streams), large river specialists (Rivers), and ubiquitous species known to inhabit both small streams and large rivers (Ubiquitous) (Appendix S1).

All sites were characterized by five regional (river basin membership), stream reach (stream width) and local (percentage of coarse substratum, litter and wood) environmental attributes that are known to be the main determinants of fish assemblage richness and composition (Jackson et al. 2001; Bojsen and Barriga 2002; Wright and Flecker 2004; Casatti and Teresa 2012). The river membership (i.e. name of the river basin) accounted for the regional scale effect. Stream width was an average measurement derived from measurements taken on three to five transversal transects according to the length of the section. Stream width represented the location of the sites in the river continuum, as testified by the significant correlation between stream width and distance from the source (Pearson correlation $r = 0.63$, $p < 0.001$). It hence accounted for the reach scale effect. At the local scale, the percentage of coarse substrate (i.e. pebbles and boulders) indicated the stream bottom substrate granulometry, but also acted as a surrogate for water velocity. The abundance of shelters was estimated by the percentage of litter and wood (woody debris and tree roots) covering the bottom. The three local habitat variables (percentage of coarse substrate, litter and wood) were visually estimated.

Data analysis

We calculated overall community descriptors such as fish species richness and fish abundance per surface unit (i.e. the number of fish per square meter). We then used species occurrences to assess differences in fish assemblage composition between reference sites and those subjected to the three types of anthropogenic disturbances. We then used a Principal Component Analysis (PCA) to ordinate the assemblages according to their taxonomic or functional composition. To avoid an undue influence of rare species in the PCA based on species identity, we only considered the species present in at least 10 % of sites, and hence retained 46 out of the 158 species collected. The PCA based on fish functional composition was based on the number of species belonging to each trophic guild (i.e. omnivorous, piscivorous and phytophagous) and to each habitat (i.e. stream specialist, main river specialist or ubiquitous). The mean maximum standard length of all species per site was also used as a functional descriptor to detect a potential disturbance effect on fish size, as it was previously shown that man-made disturbances can affect the size structure of fish assemblages (Blanchet et al. 2010; Brosse et al. 2011). All the 158 collected species were hence considered in this functional PCA. To test and illustrate whether the taxonomic and functional composition of assemblages differs according to disturbances, we represented the centroid of the sites belonging to each disturbance type. Differences between centroids were tested using a pairwise multivariate analysis of variance (pairwise MANOVA).

We then analysed the impact of anthropogenic disturbances over the entire set of sampling sites, as in a previous study, we did not find any clear physical or chemical typology for these streams, but rather a continuum of environmental conditions (Dedieu et al. 2014). Hence, according to Hermoso and Linke (2012), rather than analysing human impacts in different environmental types (type specific approach) we here preferred to use a continuum approach (or site specific approach) where we analysed human impacts on the taxonomic and functional composition of fish assemblages. To avoid bias due to the effect of environmental characteristics of the sites, we used a permutational multivariate analysis of variance (permutational MANOVA) (McArdle and Anderson 2001) that allows determining the impact of disturbances on fish assemblages while controlling the effect of natural environmental variability. Permutational MANOVA is an analysis of variance using distance matrices performed by the function 'adonis' of the package 'VEGAN' in R software (Oksanen et al. 2013; R Core Team 2015). This function partitions sums of squares using metric or semimetric distance matrices. The significance of the test was provided by *F*-tests based on the sequential sums of squares from 100,000 permutations of the raw data. In such a procedure, the order of non-orthogonal variables impacts the outcome of significance testing. We hence conserved the sequence of environmental filters from large scale to local scale (Jackson et al. 2001) in this analysis, to sequentially remove the effects of the environmental variables on the fish assemblages. The disturbance type was the last variable introduced to measure the pure effect of disturbances on fish assemblages after accounting for environmental variability. In other words, the permutational MANOVA determines how human disturbances affect the variance unexplained by the environmental variables introduced earlier in the analysis. That procedure was conducted separately for the three types of disturbance (i.e. reduced impact logging, current gold-mining and former gold-mining).

Finally, we determined how disturbances affect functional metrics (i.e. trophic guild, habitat, mean fish body size), after accounting for environmental variability. To do this, we ran Generalized Linear Models (GLMs) to predict each functional metric using the five regional, reach and local environmental descriptors as explanatory variables. The residuals (i.e. the information unexplained by environmental characteristics) of those models were then plotted for each disturbance type, and hence account for the pure effect of each disturbance type on fish functional metrics. Differences between disturbance types were tested using the pairwise Wilcoxon test.

Results

Reference, logged, currently mined and formerly mined sites showed similar environmental characteristics (Table 1). Stream width, percentage of coverage of wood and percentage of coverage of litter did not or only marginally differed between stream types (Kruskall-Wallis test $p > 0.05$ for stream width and percentage of wood and $p = 0.03$ for litter). Currently and formerly gold-mined sites only differed from references by a higher percentage of coarse substrate (Kruskall-Wallis test $p = 0.002$; Table 1).

A total of 16,219 fishes belonging to 158 species (30 families from eight orders) were collected (the list of species is provided in Appendix S1). No significant difference was apparent in either species richness (mean (±SD) = 13.6 (±7.1)) or fish abundance per square meter (mean (SD) = 1.4 (±1.2) fish m^{-2}) between site types (Kruskall-Wallis test, $p > 0.1$). The species turnover between reference sites was high (mean Jaccard dissimilarity index = 0.87), due to the biogeographic history of the region (see Methods), justifying therefore the use of a regional effect (i.e. basin identity) in our analyses to control biogeographic variability.

Patterns of fish assemblage composition between site types derived from the two first axes of the PCA (Fig. 2) clearly distinguished a shift in taxonomic and functional assemblage composition between reference and currently gold-mined sites and between reference sites and formerly gold-mined sites (pairwise MANOVA, $p < 0.01$ for both

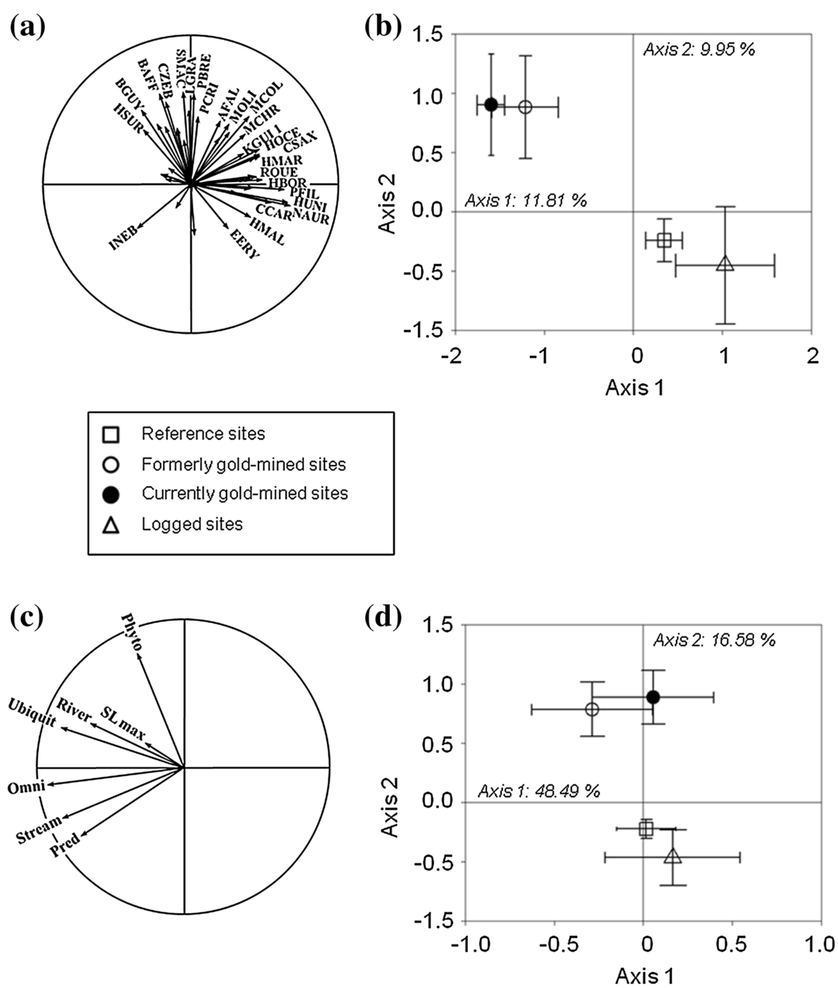

Fig. 2 Graphical representation of the first two axes of the Principal Component Analyses (PCA) performed with taxonomic (**a**, **b**; See Appendix S1 for species codes, for reasons of clarity, a species code was reported for only the 25 most influential species) and functional (**c**, **d**) data. Phyto represent the *number* of Phytophagous species by site, Omni and Pred the number of omnivorous and predatory species, and Ubiquit the number of ubiquitous species inhabiting both rivers and streams. SL max is the mean of species maximum standard length at each site. **a**, **c** Correlation circle showing the influence of species (**a**) and of functional traits (**c**) on the two first axes of the PCA. **b**, **d** Centroids, with whiskers representing SD summarising reference, reduced impact logging, formerly gold-mined and currently gold-mined sites positioned in the two first axes of the PCA based on taxonomic (**b**) and functional (**d**) data. *Symbols* represent anthropogenic disturbances, Logged sites refers to sites subjected to reduced impact logging

taxonomy and function). On the contrary, the fish assemblages from the sites subjected to reduced impact logging did not significantly differ from those observed at the reference sites (pairwise MANOVA, $p = 0.51$ for taxonomy and $p = 0.58$ for function).

The differences in fish taxonomic composition between site types still holds after accounting for basin identity, stream gradient and local habitat (permutational MANOVA, $p < 0.01$, Fig. 3a). The former and current gold-mining effect ($F = 5.24$ and 5.82, respectively) was two times higher than reduced impact logging ($F = 2.41$). The impact of the gold-mining effect was similar to that of fish shelters (i.e. wood and litter). The functional structure of fish assemblages was less impacted than the taxonomy. The effects of reduced impact logging and former gold-mining disturbances were not significant ($p = 0.32$, $F = 0.98$ and $p = 0.47$, $F = 0.47$, for reduced logging and former gold-mining, respectively), although the current gold-mining effect remained significant ($p = 0.02$, $F = 4.67$). Like for taxonomy, the effect of current gold-mining remained of a similar magnitude as shelters (Fig. 3b).

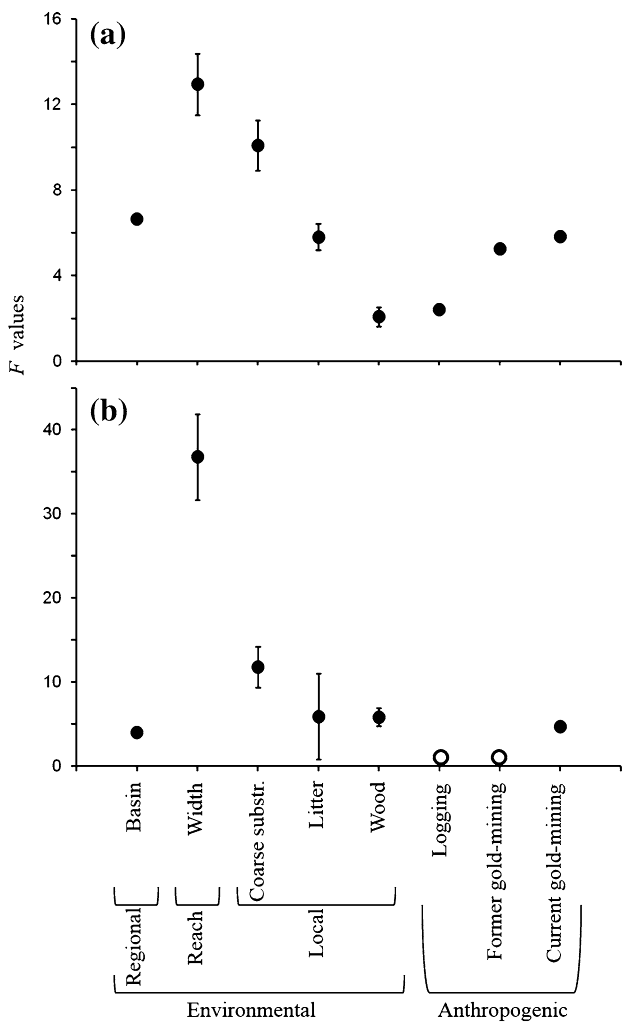

Fig. 3 Results of the permutational MANOVA. *F* values represent the importance of environmental and disturbance variables on fish assemblage taxonomy (**a**) and function (**b**). For each disturbance type, a permutational MANOVA was built with the same regional, reach and local environmental variables introduced sequentially, and the disturbance introduced as the last variable. The mean of the three *F* values with whiskers representing SD is presented for environmental variables (derived from the three models testing the effect of each disturbance independently). *Filled circles* indicate a significant structuring effect on fish assemblages ($p < 0.05$), and *empty circles* indicate a non-significant effect ($p > 0.05$). Coarse substr. refer to the percentage of coverage of coarse substrates (i.e. pebbles and boulders); Logging refers to sites subjected to reduced impact logging

Analysing the residuals of the GLMs predicting each functional metric using regional, reach and local environmental descriptors as explanatory variables revealed that currently gold-mined sites host fewer stream specialist species than do reference sites ($p < 0.05$), and more ubiquitous ($p < 0.01$) and larger species ($p < 0.05$) than do reference sites. Reduced impact logging sites differed from reference sites by a lower number of phytophagous species ($p < 0.05$), whereas formerly gold-mined sites differed from reference sites by a higher number of phytophagous species ($p < 0.05$) (Fig. 4).

Discussion

Species richness is commonly used to investigate the biotic integrity of fish assemblages in temperate regions (Breine et al. 2004; Roset et al. 2007), but its reliability remains uncertain for Neotropical streams. Indeed, some studies showed that this metric is not sensitive to deforestation (Bojsen and Barriga 2002) and gold-mining activities (Brosse et al. 2011), whereas others found that it allows assemblage modifications to be depicted, at least those related to disturbances caused by mining (Mol and Ouboter 2004). Such discrepancies are probably due to the intensity of the disturbance, which is low enough to maintain diverse fish assemblages in streams disturbed by reduced impact logging and small-scale gold-mining. Nevertheless, these disturbances might cause species replacements and subsequent functional changes in the fish assemblages, as shown by Brosse et al. (2011) on a small, localised set of study sites in the Approuague river basin in French Guiana. Such a trend was confirmed by this study, which encompasses a much larger study area and several river basins. Both the taxonomic and functional structure of the sites disturbed by gold-mining significantly differed from the reference sites, and logging significantly affected the taxonomic structure of fish assemblages. This trend held true despite the environmental variability between sites and the natural faunistic differences between river basins.

The effect of reduced impact logging we detected is consistent with a previous study that highlighted changes in

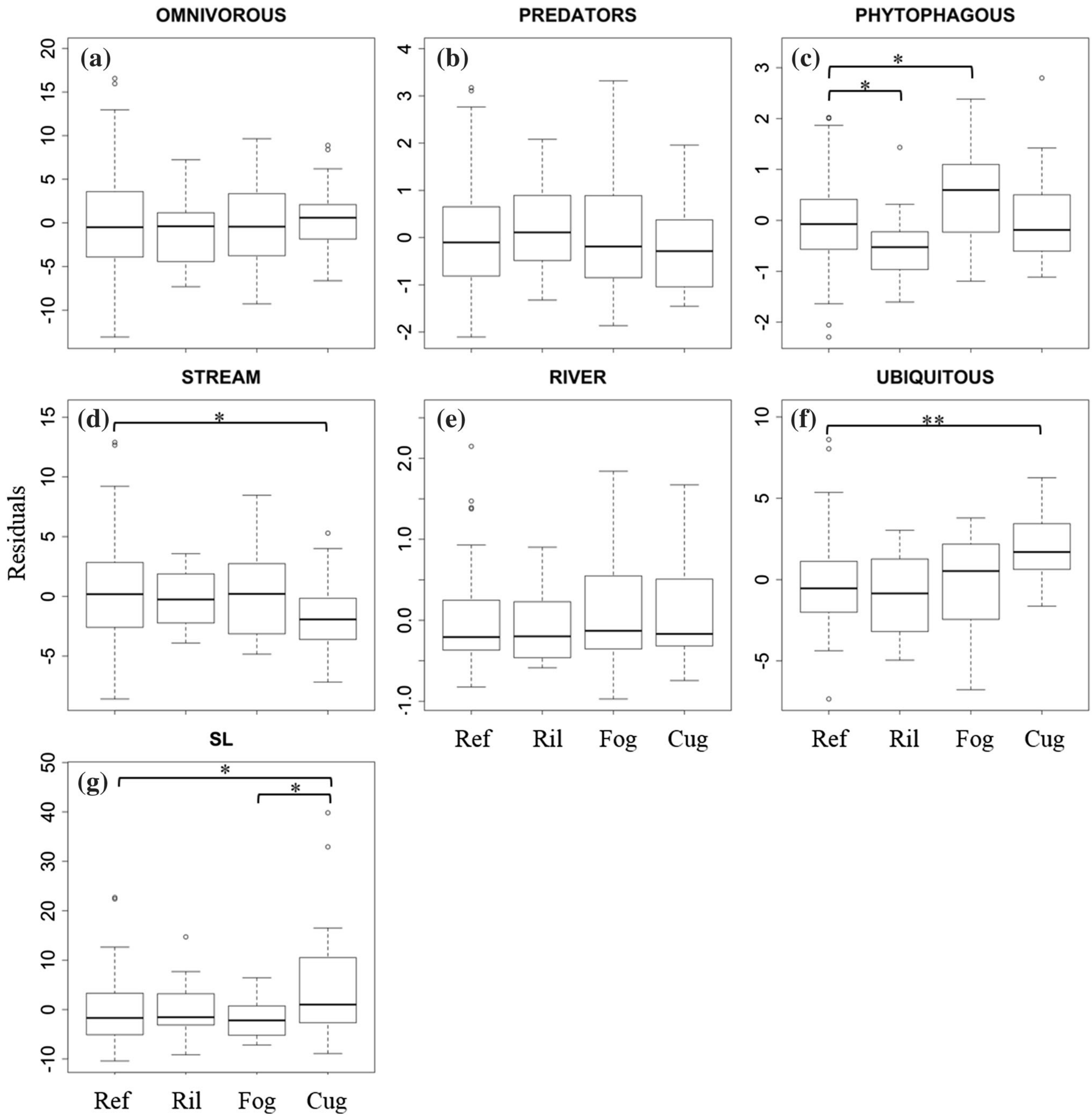

Fig. 4 Boxplots of the residual values generated by Generalised Linear Models (GLM) with environmental variables as explanatory variables and number of omnivorous (**a**), predators (**b**), phytophagous (**c**), stream specialist (**d**), river specialist (**e**), and ubiquitous (**f**) species and mean of maximum species standard length (SL, **g**) as response variables. In *each panel*, *boxplots* represent the distribution of residuals against disturbance type. *Ref* Reference, *Ril* reduced impact logging, *Fog* formerly gold-mined and *Cug* Currently gold-mined. Differences between the reference and the three impact categories, as well as between formerly and currently gold-mined sites were tested using a pairwise Wilcoxon test. *$p < 0.05$; **$p < 0.01$

fish abundance induced by reduced impact logging on 11 central Amazonian streams near Manaus (Dias et al. 2010). The taxonomic changes we observed across French Guiana were nevertheless not enough to induce a significant change in the overall fish functional structure. It can therefore be postulated that species are replaced by functionally equivalent relatives. Such a low impact is probably explained by the conservation of an undisturbed buffer zone around streams. Indeed, the riparian vegetation is known to be a major determinant in maintaining stream biodiversity and function (Lorion and Kennedy 2009; Wantzen and Mol 2013). Previous studies on the effect of reduced impact logging showed that the creation of a network of logging roads can have a pervasive indirect effect by increasing erosion and fine particle matter input to the rivers (Forman and Alexander 1998; Wantzen and Mol 2013), but can also facilitate access for hunters or fisherman (Meijaard et al. 2005; Arima et al. 2008). We are unable to disentangle these indirect effects that probably occur together. It should nevertheless be noted that phytophagous species are underrepresented in the logged sites compared to reference sites. This can be attributed to the greater erosion of roads that increases turbidity and fine particle siltation in the stream. Turbidity and siltation are known to negatively affect algal growth (Tudesque et al. 2012) and hence reduce food availability for phytophagous species, which probably explains their under-representation in the logged sites.

Gold-mining had a more prominent effect than reduced logging, as the current gold-mining effect was comparable to or higher than the abundance of shelters (i.e. litter and wood). In other words, it means that the gold-mining disturbance is comparable to the removal of shelters. Shelters are commonly accepted as a key structural component promoting fish biodiversity (Bojsen and Barriga 2002; Wright and Flecker 2004). Gold-mining hence constitutes a drastic disturbance for the fish fauna that can blur the effect of local habitat characteristics. This might be explained by the increased erosion due to gold-mining, which induces rises in turbidity and the siltation of the stream bottom (Mol and Ouboter 2004; Hammond et al. 2007; Brosse et al. 2011, Wantzen and Mol 2013). Such disturbances are prone to affect the entire ecosystem, as was shown for primary producers by Tudesque et al. (2012), and hence also affect the functional structure of the fish fauna as stream specialist species tend to be replaced by ubiquitous species probably coming from the nearby rivers. Such a result parallels and expands on a previous study on a limited set of Guianese streams (Brosse et al. 2011). Moreover, stream specialists are represented by smaller species than ubiquitous ones, which explains the trend towards an increase in fish body size at the gold-mined sites.

The harsh disturbance induced by gold-mining tends to decrease after the cessation of the mining activity. In the formerly gold-mined sites, the activity ceased a few months to 1 year before sampling (for most sites, we are unable to be more precise due to the illegal nature of the mining activity). Such a duration was sufficiently long to allow flushing of silt downstream, therefore decreasing the negative effect of siltation and turbidity. The formerly gold-mined sites recovered from a functional point of view and, contrary to our expectations, experienced an increase in the number of phytophagous species. This might be due to an increase in periphyton production caused by an increase of light intensity caused by a degradation of the riparian vegetation on the mining site (Bojsen and Barriga 2002; Lorion and Kennedy 2009; Wantzen and Mol 2013). Contrary to the functional structure, the taxonomic structure of the fish fauna in formerly mined sites remained distinct from reference sites, testifying therefore to the long duration of the disturbance effect caused by mining. It might be hypothesized that recolonisation from upstream sites or nearby tributaries was achieved by the most mobile species, therefore selecting a particular species assemblage, without changes (except for phytophagous species) in the functional structure of the assemblage. We nevertheless have no data on fish species dispersal ability to test this hypothesis.

Small-scale gold-mining can be considered a major threat to Neotropical stream fish biodiversity. Indeed, gold-mining is particularly widespread in South America (Veiga 1997; Alvarez-Berríos and Aides 2015), and is currently experiencing a dramatic increase due to the rise of gold prices that pushes illegal miners to exploit remote and pristine sites throughout the Amazon region (Hammond et al. 2007; Alvarez-Berríos and Aides 2015). For example, in the Guiana shield, a threefold increase in the number of impacted streams was recorded in the last decade, representing more than 26,000 km of impacted streams (Hammond et al. 2007; World Wildlife Fund Guianas 2012). Due to the illegal nature of the mining, it should be noted that national parks are not spared from these disturbances (Alvarez-Berríos and Aides 2015). Indeed, some of the impacted sites in this study are in nature reserves and national parks. In the same way, Mol and Ouboter (2004) reported illegal mining sites in the Brownsberg and Boven-Coesewijne reserve in Suriname, and similar disturbances were reported in Kaieteur National Park in Guyana (World Wildlife Fund Guianas 2012).

Although this study is limited to French Guiana, the consideration of a large number of sites across different river basins with distinct species pools allows us to go beyond previous local scale studies (e.g. Mol and Ouboter 2004; Dias et al. 2010; Brosse et al. 2011) and to identify major trends that hold true regardless of regional and local environmental effects. It can hence be considered that reduced impact logging has a significant, but limited impact on the stream fish fauna, contrary to illegal gold-mining which has a more pronounced detrimental effect. We hence appeal to environmental managers and governments to consider small-scale gold-mining as a major threat for biodiversity and to better regulate and control these activities that could accelerate biodiversity decline in one of the most species rich areas of the world.

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