Influence of acid-mine drainage, and its remediation, on lake water-quality and benthic invertebrate communities

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Abstract: The abandoned Aldermac Mine in Québec, Canada, has been a source of acid mine drainage to Lake Arnoux since 1946. Restoration of the site was undertaken in 2008 and completed in 2010. We compared lakewater chemistry and benthic invertebrate communities in the spring of 2010, prior to complete restoration, and in spring 2011, when acid mine drainage was no longer entering the lake. Between these years, lakewater pH increased by about one unit and the concentrations of many trace metals declined substantially. In 2010, benthic taxonomic richness increased significantly with distance from the source of contamination, whereas after restoration there was no longer a clear trend. Communities in highly contaminated stations tended to be dominated by burrowing taxa such as larvae of *Chironomus* (Chironomidae) and Oligochaeta, whereas less contaminated stations had taxonomic and functional communities that were more diverse. The year following recovery, some new taxa appeared (Trichoptera, Odonata and the Ceratopogonidae *Bezzia*), whereas the populations of an acid-tolerant *Chironomus* species declined. However, only larger individuals exhibited a significant response to pH and metal contamination.

Keywords: metals, benthos, acid-mine drainage, community structure, recovery, functional traits.

1. INTRODUCTION

Acid mine drainage (AMD) results when water, oxygen and microorganisms oxidize pyrite ore (FeS_2) in groundwater (Massmann et al. 2003) and in mine tailings (D. B. Johnson et al. 2005), thereby releasing dissolved metals in highly acidic solution (Chen et al. 2015; Massmann et al. 2003) that can alter aquatic communities downstream (DeNicola et al. 2002; Hogsden et al. 2012), in streams (Battaglia et al. 2005; Malmqvist et al. 1999) as well as in lakes (Azcue et al. 1995; A. Johnson et al. 1997) . Invertebrate communities can be altered by the acidity of the runoff (Hare 1992), toxicity due to the metals that it contains (MacCausland et al. 2007; Malmqvist et al. 1999; Perceval et al. 2006), smothering due to the deposition of iron oxides (Vuori 1995) and reductions in the rate of organic matter decomposition (Simmons et al. 2005). Without site remediation, the influences of AMD on downstream lakes and streams can remain measurable decades after the cessation of mining activity (Perceval et al. 2006).

Many methods of remediation of former mining sites have been proposed to limit acidic, metal rich, discharges (see D. B. Johnson & Hallberg (2005) for a review). Water-quality measurements are useful for evaluating the influence of remedial efforts on the pH and metal concentrations in downstream waters (DeNicola et al. 2002; SNC Lavalin 2007). However, water-quality measurements are not necessarily correlated with the responses of aquatic communities since their development can be delayed by physical changes to the environment (e.g., Mackey 1977), a lack of sufficient biomass at lower trophic levels (Ristola et al. 1999), ongoing toxicity due to trace metals (Yan et al. 1990), and a potential lag time between improvements in the quality of the water column and that of sediments (Vanbroekhoven et al. 2008). Furthermore, decreasing acidity can actually increase the concentrations of some metals in aquatic invertebrates (Croteau et al. 2002). Measurements of trace metals in invertebrates (Hare et al. 2008), as well as the evaluation of benthic or pelagic community structures (Breneman et al. 2000; Canfield et al. 1994; García-García et al. 2012) and functions (He et al. 2015), provide a more direct means of determining the biological impacts of AMD. Overall, studies of the impact of AMD on both the taxonomic and functional structure of lake communities remain scarce.

Under metal and acidic stresses, pelagic food-webs tend to become less complex with fewer species (Havens 1993), whereas benthic communities tend to be composed of fewer, more tolerant, taxa than those at circum-neutral pH (Bott et al. 2012; DeNicola et al. 2002). With effective remediation, increasing pH and declines in trace metal concentrations should favor richer and more diverse communities because metal intolerant species would be allowed to recolonize lakes. However, the recovery process can be hampered if metal concentrations in invertebrates initially increase with increasing lakewater pH (Croteau et al. 2002).

We set out to measure community recovery in a northern Quebec lake that has been subject to AMD for several decades. Copper-zinc ore was extracted from the Aldermac Mine, located 15 km west of the city of Rouyn-Noranda (Québec, Canada), between 1931 and 1943, after which time the mine was abandoned (SNC Lavalin 2007). Approximately 1.5 Mt of tailings were dispersed over 76 hectares. Fifty percent of the tailings are sulfur-rich minerals containing high concentrations of arsenic, cadmium, copper, molybdenum and zinc (SNC Lavalin 2007). Tailings were drained in large part by the Arnoux River, which carried these highly acidic (pH 2.5-3.6) and trace-metal rich waters into Lake Arnoux (SNC Lavalin 2007). In 2008, the Quebec Ministry of Natural Resources and Wildlife initiated a two-year restoration project that involved excavating and confining the acid-generating wastes then replanting trees on the site. The flow of AMD to Lake Arnoux was curtailed in 2010.

We measured changes in the chemical and biological conditions in Lake Arnoux prior to (2010) and after (2011) the cessation of AMD to monitor responses to the elimination of contamination from the Aldermac mine tailings. To assess biological changes, the taxonomic and functional composition as well as the abundance of benthic invertebrates were assessed at a series of stations situated at increasing distances downstream from the source of the acid-mine drainage. A rise in pH was expected to lead to the disappearance of acid tolerant species, the appearance of acid-intolerant species with the net result that there would be an increase in the richness and diversity of macroinvertebrate communities in Lake Arnoux as well as changes in community functional groups.

2. METHODS

2.1. Sampling sites and dates

Lake Arnoux (8.6 km²) is fed mainly by the Arnoux River, although a stream from Lake LaRochelle also flows into Lake Arnoux just prior to our station AR-4 (Fig. 1). In June 2010, we collected water and benthic invertebrates at 8 stations (Fig. 1) in Lake Arnoux (AR-1 to AR-5), in Arnoux Bay of downstream Lake Dasserat (AR-7) and at a distant station in Lake Dasserat (DAS), hereinafter considered as the reference station. In June 2011, we collected water at 4 of the 8 stations (AR-2, AR-3, AR-5 and DAS, data from AR-1 were unfortunately lost) and invertebrates at 6 of the 8 stations (AR-1, AR-2, AR-3, AR-5, AR-6, AR-7 and DAS). Distances between stations were calculated as “the fish swims”, i.e., by the shortest path in the lake (Tab. 1). No heavy precipitation (<6 mm) was recorded prior to and during the sampling campaigns in both years (Government of Canada 2017).

Table 1: Distance of sampling stations downstream from the contamination source (Arnoux River).

Station	Distance downstream (km)
AR-1	0
AR-2	0.8
AR-3	2.7
AR-4	4.6
AR-5	4.7
AR-6	5.5
AR-7	6.2
DAS	12

Our closest station to the AMD source, AR-1, is situated at the mouth of the Arnoux River, which was the source of the AMD to Lake Arnoux, whereas the station most distant from the AMD (DAS) is located about 12 km from AR-1 at the north-eastern end of Lake Dasserat (Fig. 1). In Lake Dasserat, prior to remediation, negative effects of the AMD drainage on a population of metal-sensitive invertebrates (bivalves) were reported at a station about 2 km south of our station DAS (Goulet et al. 2009; Perceval et al. 2006). Furthermore, prior to site restoration, Zn concentrations were reported to be moderately high in water and sediments at a site in Lake Dasserat (Borgmann et al. 2004), compared to those measured in other lakes in the region, although mayflies were reported to persist in this lake (Borgmann et al. 2004) (Borgmann et al. 2004) as were large-sized yellow perch (*Perca flavescens*) (Kövecses et al. 2005). In fact, Lake Dasserat is heterogeneous with respect to metal contamination with its northwestern and southern parts being little contaminated and its central and eastern parts being moderately contaminated due to AMD from Lake Arnoux (Fig. 1).

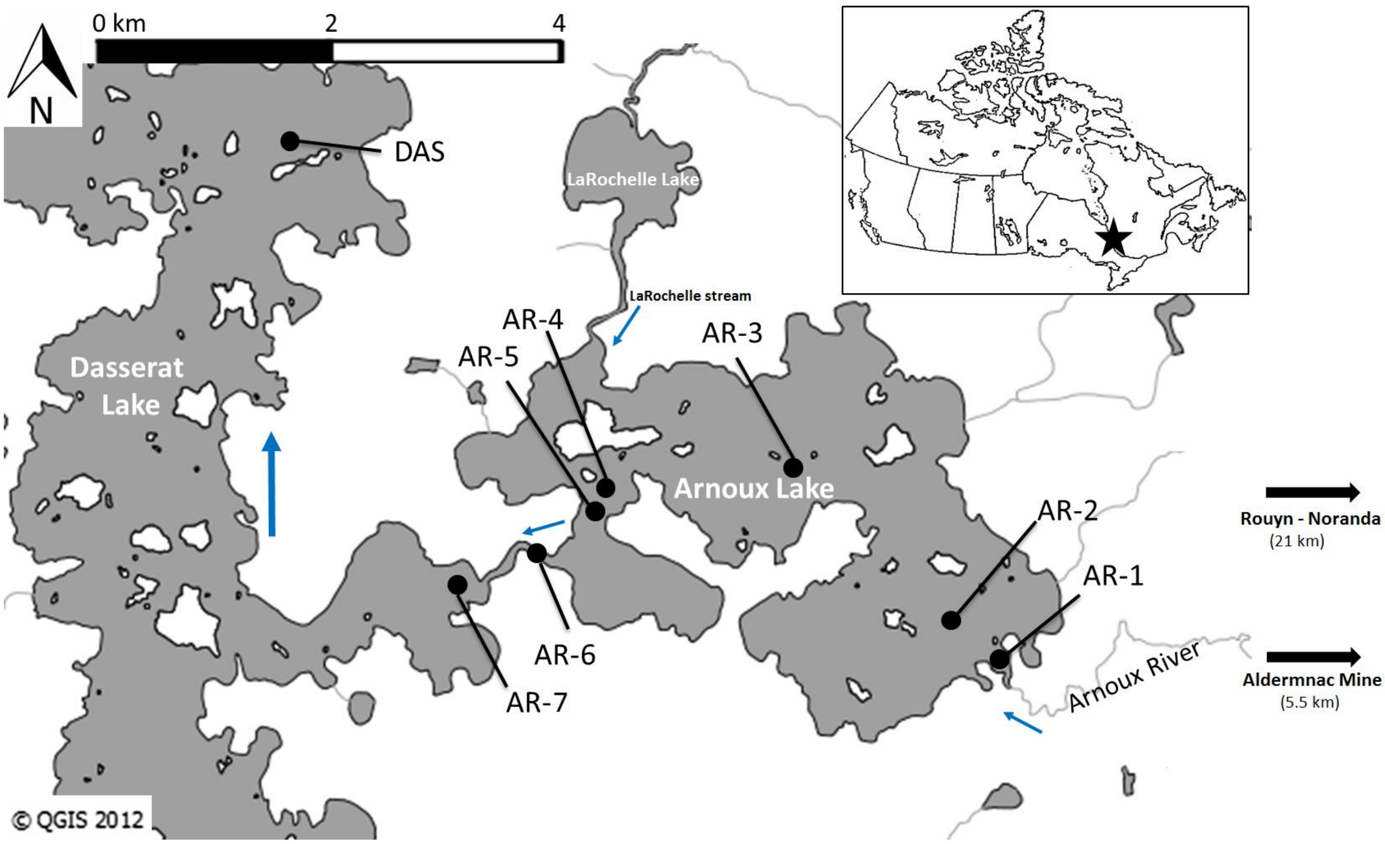

Fig. 1 Sampling stations in Lake Arnoux (AR-1 to AR-5), in Arnoux Bay of Lake Dasserat (AR-7) and at a distant station in northern Lake Dasserat (DAS). Station AR-1 is located at the mouth of the Arnoux River, which was fed by runoff from the mine tailings. Thin arrows indicate the direction of water flow.

2.2. Lakewater collection and analysis

Details of lakewater collection and analysis are given in Ponton and Hare (2009, 2013). Briefly, lab-ware used for the collection, storage and analysis of lakewater was soaked in 15% nitric acid and rinsed in ultra-pure water prior to use. Lakewater was filtered in situ using Plexiglas diffusion samplers composed of eight 4-mL cells filled with ultrapure water, and covered with a polysulfone membrane (GelmanHT-200; 0.2 µm pore size). At each station, diffusion samplers were submerged 1 m below the surface and left for a minimum of 3 days to reach a steady state between the concentrations of total dissolved elements in sampler cells and surrounding lakewater. On collection, water was removed from sampler cells using a pipet and injected into 4-mL (anions; Cl, NO_3, SO_4) or 16-mL (cations; Na, Mg, Al, K, Ca, Mn, Fe, Co, Ni, Cu, Zn, Cd, Ba) high-density polyethylene (HDPE) bottles. Water for dissolved organic carbon (DOC) measurements was removed using a NaOH (5 mM) rinsed, plastic tipped, pipet then injected into dark glass bottles that had been washed in NaOH, rinsed, heated to 400°C and then rinsed in ultrapure water.

Anions were measured by ion chromatography (Dionex, ICS-2000 system; AS-18 column). Major cations were measured by AES (Atomic Emission Spectroscopy) and trace metals were measured by inductively coupled plasma - mass spectrometry (Thermo Elemental, X Series). Dissolved organic carbon was transformed into CO_2 and measured on a Shimadzu TOC-5000A. Lakewater pH was measured at the time of sampler collection in the peepers and at the surface using a portable pH meter (Hanna Instruments).

2.3. Collection and analysis of benthic invertebrates

Benthic invertebrates were collected using an Ekman grab (23 x 15 x 15 cm). Fine sediment was removed by sieving samples (3 per station) through a 0.5-mm mesh net and the remaining material was preserved in 10% formaldehyde solution. The depth of all stations ranged from 3-4 meters. The water was clear at every station in 2010, but the turbidity increased in 2011. No visible organic matter was present on the bottom of Lake Arnoux, with the exception of some debris near the stream flowing into Lake Dasserat. A thick layer of brown rusty-colored iron oxyhydroxydes was observable at station AR1, as well as all other stations in Lake Arnoux albeit in a thin layer.

Table 2 : list of traits considered in our study and their attributes

Trait	Attribute	Code
Functional feeding group	- Predators - Gatherers - Shredders - Filterers - Scrapers	- Pred - Gather - Shred - Filter - Scrap
Habit trait group	- Sprawlers - Burrowers - Swimmers - Clingers - Climbers	- Sprawl - Burrow - Swim - Cling - Climb
Life cycle duration	- =< 1 year - >1year	- VitCycle1 - VitCycle2
Generation per year	- >1 - 1 - <1	- Gen1 - Gen2 - Gen3
Main dispersion tactics	- Aquatique passive - Aquatique active - Aerial passive - Aerial Active	- AquaPass - AquaAct - AeriPass - AeriAct
Food	- Small debris - Microphytes - Macrophytes - Microinvertebrates - Macroinvertebrates	- Debris - Microph - Macroph - MicroInv - MacroInv
Respiration	- Trans-tegument - Gills	- Teg - Gills
Maximal size	- 5-10 mm - 10-20 mm - 20-40 mm - 40-80mm	- MaxSiz_5-10 - MaxSiz_10-20 - MaxSiz_20-40 - MaxSiz_40-80

In the laboratory, invertebrates were sorted and identified under a dissecting microscope and then preserved in 70% ethanol. Chironomidae larvae were mounted on microscope slides for detailed examination. Insecta and Gastropoda were identified to the genus level (Wiederholm 1983, Merritt et al. 2008), whereas Oligochaeta and Nematoda were not determined further.

We determined a set of traits with a membership value for each trait attribute, for each taxon (Tab. 2), based on information provided in Pennak (1978), Wiederholm (1983), Barbour et al. (1999), Tachet et al. (2000), Mandaville (2002) and Merritt et al. (2008), adapted to the taxa living under local environmental conditions. See online Resource 1 for the membership values of each attributes of each traits for every taxon, and Tab. 2 for the code of each attribute.

2.4. Statistics

All statistical tests were conducted using R 3.3.1 (R Development Core Team 2016).

Lakewater chemistry was compared between 2010 and 2011 using Wilcoxon signed rank paired test for each variable. Comparisons among benthic communities at various stations are based on total abundance (individuals in 3 samples), taxonomic richness (total number of taxa in 3 samples) and two biotic indexes: the Shannon-Wiener Index $H'=-\sum p_i*\log_2 p_i$ (with p_i = relative proportion of the considered taxon), which is sensitive to rare species and reportedly useful for characterizing benthic communities in streams contaminated by mining activities (Wu et al. 2011), and the Simpson reciprocal Index $1/D=1/(1-\sum p_i^2)$, which is sensitive to abundant species;

values closest to 1 are most diverse. For each site sampled, differences in diversity-indices between the two years was tested with a permutation test with null model based on our data.

Lastly, we performed an analysis combining the fourth-square method (Legendre et al. 1997), which tests the pair-to-pair significance of environmental variables and traits, and the RLQ analysis (Dolédec et al. 1996), which synthesizes multivariate structures, as described in Dray et al. (2014), to highlight how the environmental variables filter the species traits in the conditions of lakes under influence of AMD. The fourth-corner/RLQ analysis considers simultaneously the information provided by species abundances (Table L), traits related to these species (Table Q) and the environmental parameters (Table R), thereby allowing the simultaneous analysis of these three types of information, and is the most integrated method in analyses of traits-environment relationship (Kleyer et al. 2012).

3. RESULTS

3.1. Water chemistry

In 2010, the concentrations of trace metals and major ions (Fig. 2) were highest at station AR-1, whereas pH was lowest at this site (Fig. 3). Values of these variables changed markedly at the next station downstream (AR-2; Fig. 2 and 3). At stations further downstream, the concentrations of trace metals and major ions changed little. The pH increased continuously (Fig. 3) from AR-1 (pH =2.4) to AR-5 (pH= 4.36). Values of pH >6 were measured only at the two stations in Lake Dasserat. See online Resource 2 for water chemistry and pH measurements.

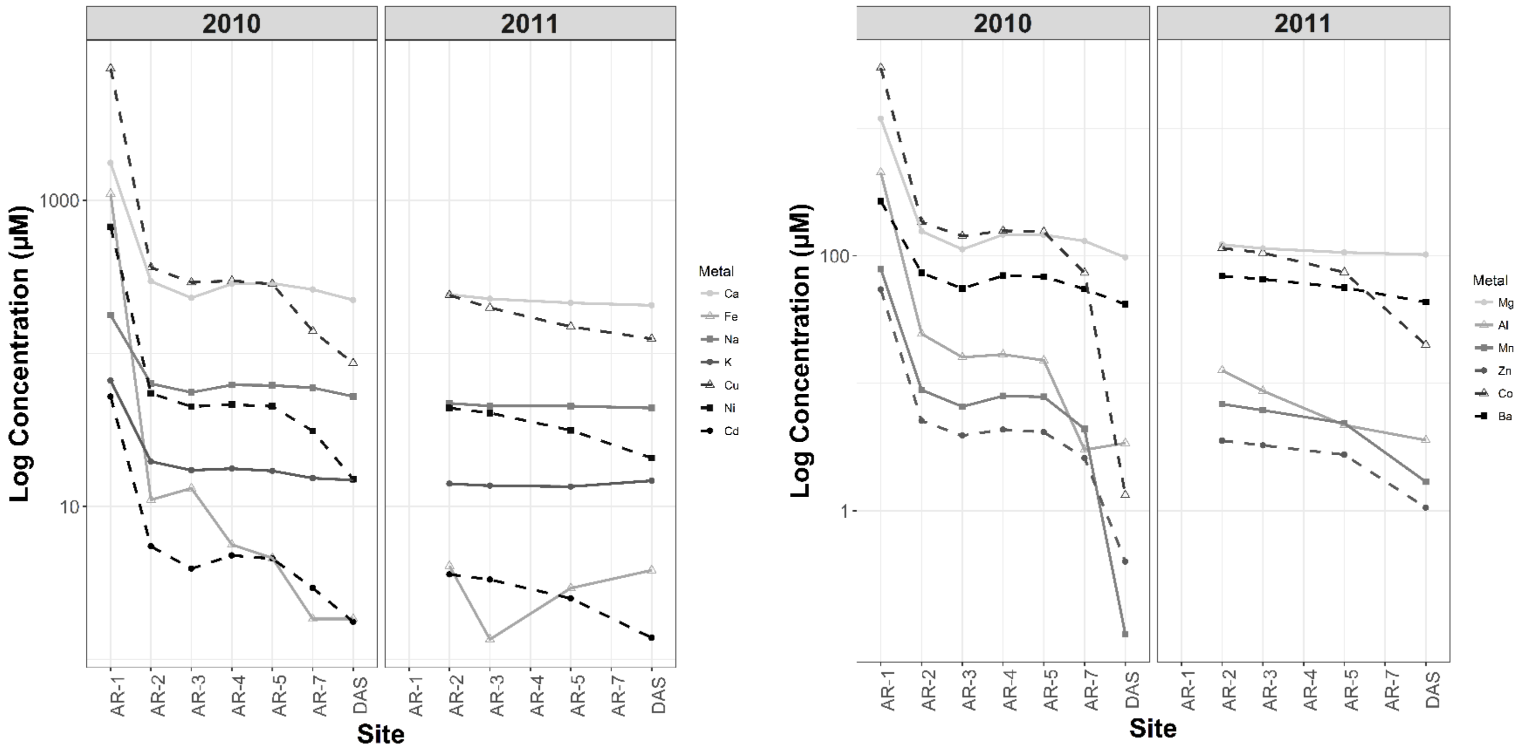

Fig. 2 Spatial changes in water chemistry in 2010 and 2011 in Lake Arnoux, from the station the closest to the contamination source (AR-1) to the most distant station (AR-7) and the reference station in Lake Dasserat (DAS). Metals were separated into two groups for plotting purposes only.

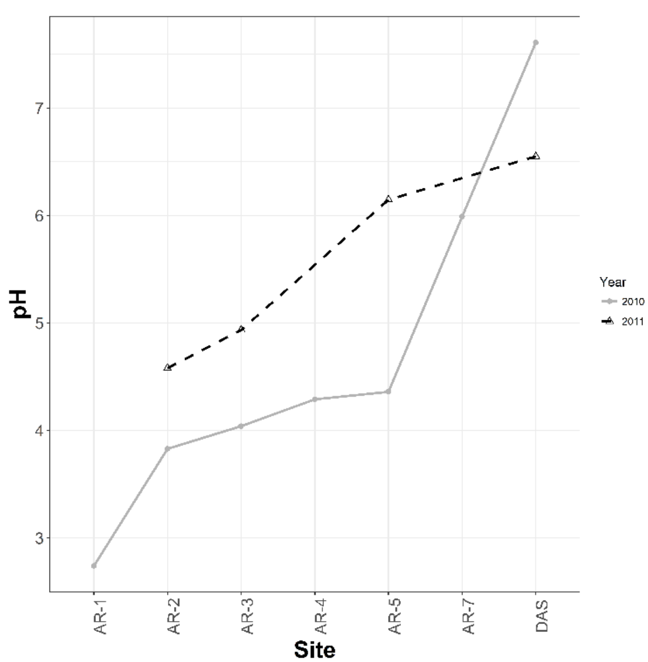

Fig. 3 Changes in pH between 2010 (broken line) and 2011 (solid line).

At the four stations sampled in 2011, the concentrations of most chemical variables had decreased from those measured in 2010 (Fig. 4, Tab. 3), whereas pH values had increased at most stations (Fig. 3, Tab. 3). Exceptionally, there were only minor changes in a few elements (e.g., Mg: +1.6%, Ba: -5.5%) and in northern Lake Dasserat (DAS) we measured small increases in the concentrations of some cations (Mn, Fe, Mg, Co, Cu) and a slight decline in pH. These differences in water chemistry were significant for all stations (Wilcoxon signed rank test, $p < 0.05$). Concentrations of DOC increased at stations AR-2 and AR-3, whereas they decreased at stations AR-5 and DAS (Online Resource 2).

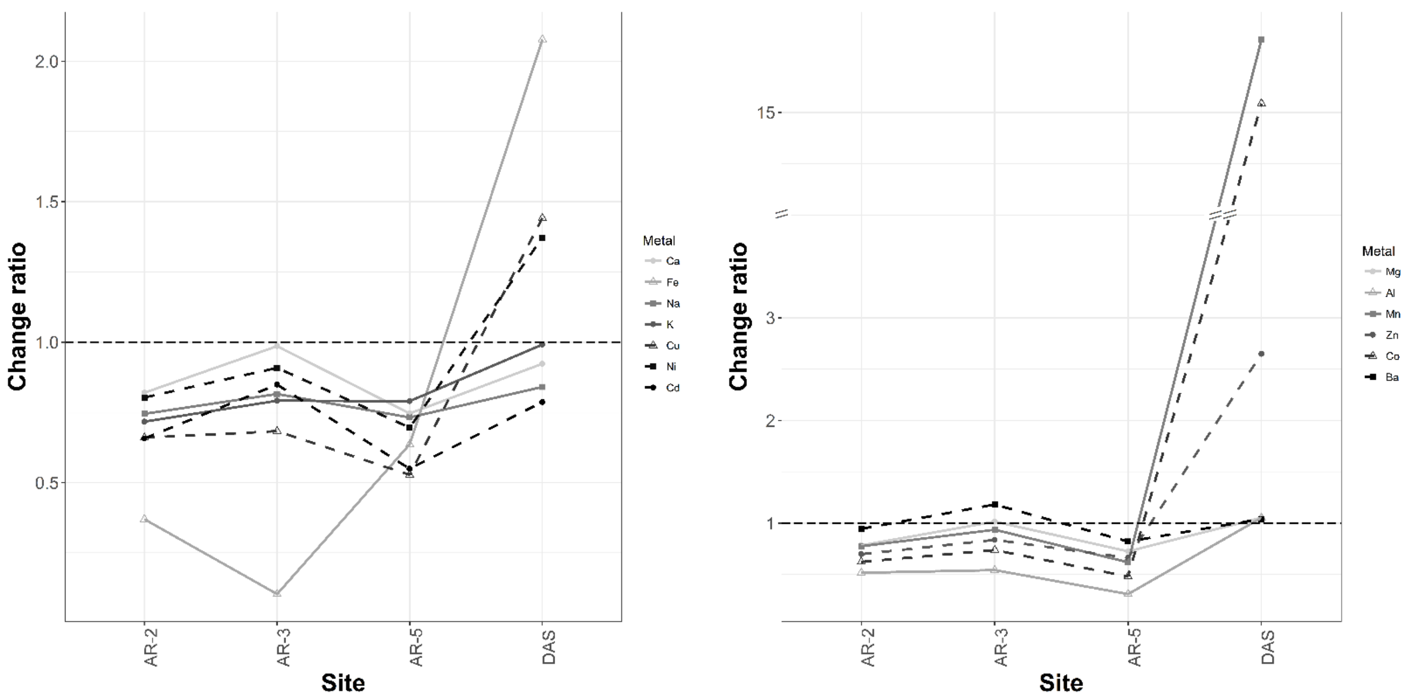

Fig. 4 Changes in the ratio of trace metal concentrations between 2010 and 2011 at 3 stations in Lake Arnoux and at the station most distant from the contamination source in Lake Dasserat (DAS). A ratio of 1 indicates no change. Metals were separated into two groups for plotting purposes only.

Table 3: Differences in the chemistry of Lake Arnoux water between 2010 and 2011.

	pH	DOC	SO_4	CO_3	Cl	NO_3	Ca	Mg	Fe	Al	Na	Mn	K	Zn	Cu	Co	Ni	Ba	Cd
	units	mg/L	mM				mM								µM				
AR-2	0.75	2.27	-191	-24	-26.2	-13.9	-53.1	-33.6	-7	-11.8	-16.2	-2	-5.6	-1.5	-124	-69.3	-10.8	-4.1	-1,9
		(+343%)	(-31%)	(-71%)	(-68%)	(-51%)	(-18%)	(-22%)	(-63%)	(-48%)	(-26%)	(-22%)	(-28%)	(-30%)	(-34%)	(-38%)	(-20%)	(-5.5%)	(-34%)
AR-3	0.9	0.57	-71.5	-20.7	-19.5	0.15	-3.27	1.75	-11.8	-7.3	-10.3	-0.42	-3.6	-0.63	-92.1	-37.4	-4.1	10.1	-0.6
		(+24%)	(-15%)	(-67%)	(-97%)	(+0.1%)	(-1.4%)	(+1.6%)	(-90%)	(-46%)	(-18%)	(-6.4%)	(-21%)	(-16%)	(-32%)	(-26%)	(-9.2%)	(+18%)	(-15%)
AR-5	1.79	-1.02	-169	-17.4	-30.5	-4	-72.6	-39.9	-1.68	-10.4	-16.6	-2.98	-3.6	-1.39	-134	-80.1	-13.7	-12.2	-2.1
		(-22%)	(-33%)	(-64%)	(-85%)	(18%)	(-25%)	(27%)	(-36%)	(-69%)	(-27%)	(-38%)	(-21%)	(-34%)	(-47%)	(52%)	(-30%)	(-18%)	(-45%)
DAS	-1.06	-18.67	132	-183	-5.5	0.23	-17.1	5.2	1.99	0.18	-8.3	1.57	-0.12	0.66	38	18.6	5.6	1.71	-0.38
		(-80%)	(+86%)	(-85%)	(-42%)	(+1.7%)	(-7.7%)	(+5.3%)	(+108%)	(-16%)	(-16%)	(+1471%)	(-0.9%)	(+165%)	(+44%)	(+1409%)	(+37%)	(+4.1%)	(-21%)

3.2. Benthic invertebrates

In total, we identified 1384 individuals from 28 taxa (including 25 insect genera; Tab. 4). Overall, the genera with the largest numbers of individuals were the chironomids (Diptera) *Chironomus* (524), *Procladius* (247) and *Tanytarsus* (156). Taxonomic richness varied from a low of 2 taxa per station (AR-1 and AR-2 in 2010) to a high of 14 taxa per station (AR-7 and DAS in 2011).

With the exception of AR-1 in 2011, where invertebrates were absent, the total abundance at a given station varied from 22 and 299 individuals (i.e., 222 to 2889 individuals /m^2) in 2010, and from 77 to 186 individuals (i.e., 744 to 1797 individuals /m^2) in 2011, but there were no trends with distance from the source in a given year or between years (Wilcoxon signed rank test, p = 0.06). Richness increased with distance from the source in both years (Fig. 5) and was significantly higher in 2011 than in 2010 (Wilcoxon signed rank test, p = 0.02). Dragonflies, stoneflies and the genus *Bezzia* (Diptera Ceratopogonidae) were collected only in 2011 (Tab. 4). The biodiversity index AvTD decreased with distance from the source in 2010, whereas VarTD did not show a trend for that year. In 2011, both AvTD and VarTD curves did not show clear trends. Values of the Shannon and Simpson diversity indexes increased downstream from the source in both years (Figure 5) with the Shannon Index being significantly different between years for all stations (all *p-values* =< 0.01) and the Simpson Index being significantly different between years at stations AR-2 (*p-values* = 0.012), AR-3 (*p-values* = 0.01) and AR-5 (*p-values* = 7.10^{-3}) but not at AR-7 and DAS (*p-values* <0.28).

Table 4: Abundance of benthic invertebrates (number of individuals/m^2) in 3 grab samples per station in 2010 and 2011.

					Epheme-roptera		Odonata				Megaloptera	Trichoptera				Diptera													
				Gastropoda	Polymitar-		Corduliidae	Libellulidae		Coenagrio-nidae	Sialidae	Polycentro-podidae			Leptoceridae	Chironomidae												Chaoboridae	Ceratopo-
Year	Station	Nematoda	Oligochaeta	*Physaacuta*	*Ephoron*	*Ephemeropt.sp*	*Somatochlora*	*Sympetrum*	*Leucorrhinia*	*Coenagrion/Enallagma*	*Sialis*	*Plectrocnemia*	*Holocentropus*	*Polycentropus*	*Oecetis*	*Chironomus*	*Tanytarsus*	*Cladotanytarsus*	*Polypedilum*	*Glyptotendipes*	*Ablabesmyia*	*Djalmabatista*	*Clinotanypus*	*Psectrocladius*	*Psectrotanypus*	*Dicrotentipes*	*Procladius*	*Chaoborus*	*Bezzia*
	AR-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2879	-	-	-	-	-	-	-	-	-	-	-	10	-
	AR-2	-	184	-	-	-	-	-	-	-	-	-	-	-	-	415	-	-	-	-	-	-	-	-	-	-	-	-	-
	AR-3	-	386	-	-	10	-	-	-	-	-	-	-	-	-	242	48	-	-	-	-	-	-	-	-	-	-	-	-
	AR-4	-	97	-	-	-	-	-	-	-	-	-	-	-	-	686	367	-	-	-	-	-	-	-	-	-	10	29	-
	AR-5	-	135	-	-	-	-	-	-	-	-	-	-	-	-	222	39	-	-	-	-	-	-	-	-	-	106	10	-
	AR-6	-	58	-	-	-	-	-	-	-	77	-	-	-	-	48	-	-	-	-	-	-	-	-	-	-	271	10	-
	AR-7	19	377	-	-	-	-	-	-	-	-	-	-	-	-	203	425	-	48	48	-	19	-	-	-	-	261	-	-
2010	DAS	-	-	-	10	-	-	-	-	-	10	-	-	-	-	19	29	19	-	87	-	-	-	-	-	-	87	48	-
	AR-2	10	309	-	-	-	-	-	-	10	19	106	-	19	-	10	-	-	-	-	-	-	-	-	-	-	10	-	-
	AR-3	29	348	-	-	-	-	-	-	-	-	261	126	68	-	106	242	-	-	-	-	-	-	-	-	-	522	-	97
	AR-5	19	87	-	-	-	-	-	-	-	-	19	10	10	10	203	126	-	-	-	-	-	39	19	-	-	135	29	39
	AR-7	19	39	-	-	-	10	29	10	-	-	106	97	29	58	29	203	-	-	-	29	-	-	-	-	164	609	-	319
2011	DAS	19	68	9	-	-	10	-	-	-	10	39	106	-	77	-	29	-	68	-	-	-	-	29	19	19	376	-	329

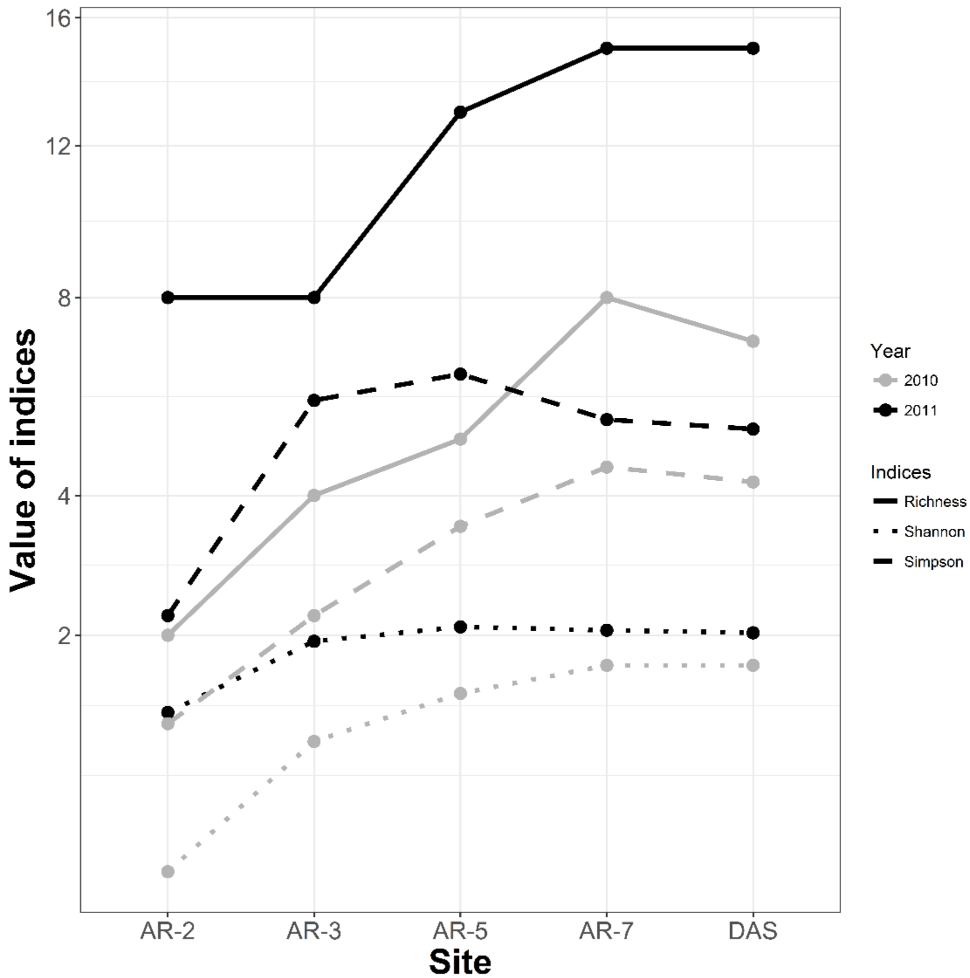

Fig. 5 Trends in: taxonomic richness (solid lines), Shannon Index (dotted lines) and Simpson Index (dashed lines) at stations sampled in 2010 (black lines) and in 2011 (grey lines). The Shannon Index was significantly different between years at all stations (all *p-values* =< 0.01), whereas the Simpson index was significantly different between years at stations AR-2, AR-3 and AR-5 (*p-values* < 0.012).

3.3. RLQ/ fourth-corner analysis

There were few connections between the traits of aquatic invertebrates and the habitat variables (Fig. 6). Gatherers and predators exhibited opposite responses: the gatherers and the predators were respectively positively and negatively correlated with the year 2010 and the concentration in Cl^-, and respectively negatively and positively correlated with 2011. Lastly, only individuals with a 40-80 mm maximum size, mainly represented by *Chironomus* sp., exhibited a negative correlation with pH and positive correlations with various metals and ions. Indeed, in 2010, gatherers and filterers (*Chironomus, Tanytarsus,* Oligochaeta) were overwhelmingly dominant at the four stations closest to the contamination source (AR-1 to AR-4), whereas shredders were present only at distant stations (Tab. 4). In 2011, predators were found closer to the contamination source (at station AR-2), such that predators, gatherers and filterers were well represented at the 4 stations sampled.

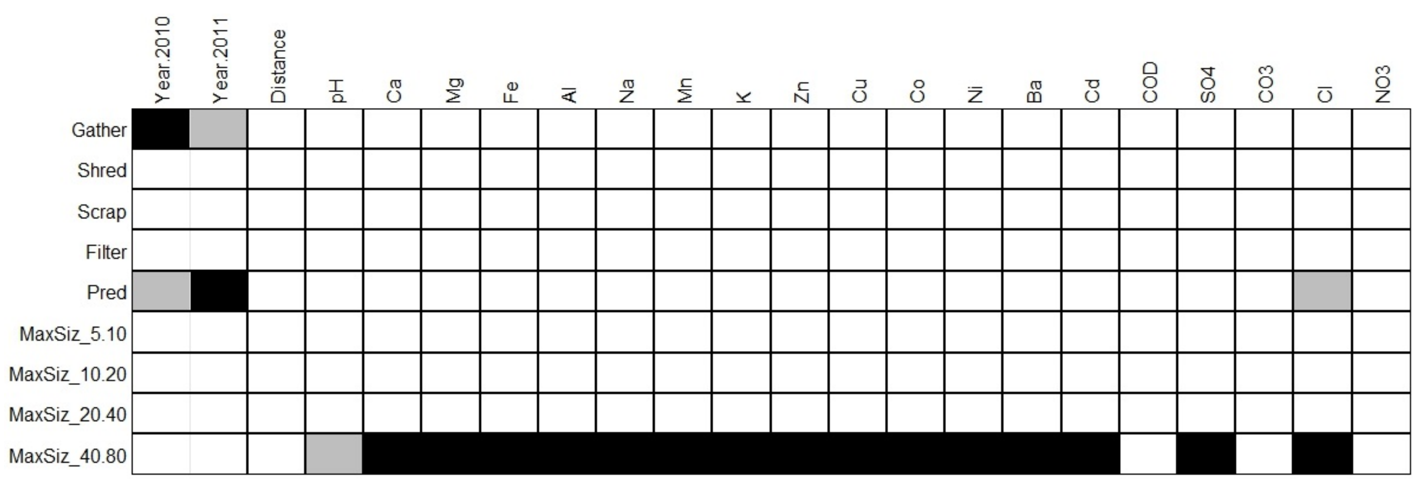

Fig. 6 Fourth corners/RLQ analysis showing positive (grey) or negative (black) significant relationships between traits (Functional feeding group, Maximal size) and environmental parameters. The other traits considered showed no significant relationships and thus are not shown.

4. DISCUSSION

Prior to the cessation of AMD, in 2010, high concentrations of trace metals and major ions were measured in Lake Arnoux at the station closest to the contamination source (AR-1), which also had the lowest pH. There was a sharp decrease in trace metal concentrations and an increase in pH at the next station, then little change thereafter. Dissolved metal concentrations were highest at the first few stations. The same general trend was reported in 2007 for Lake Arnoux (SNC Lavalin 2007). High concentrations of metals, sulfate and acidity are typical of acid-mine drainage (Bhattacharya et al. 2006; Schaider et al. 2014).

Following remediation, in 2011, there was a strong decrease in the concentrations of most major ions and trace metals (e.g., Fe: -90%) and pH values had increased by 0.75 to 1.79 units at stations in Lake Arnoux. Overall, these chemical changes suggest that within only a year of completion of the remediation work on the Aldermac Mine site, there was a substantial reduction in contaminant concentrations and the acidity of the water entering Lake Arnoux via the Arnoux River. The increasing concentrations of some metals (Fe, Cu and Ni) at the DAS station, linked with a lower pH that likely increased metal mobility, suggests that the positive effects of a reduction in AMD has not yet been manifested at this distant station (12 km from the source of the AMD). Furthermore, the water renewal time of Lake Dasserat is almost 1 year (Couillard et al. 2004), which likely also contributes to the lag in visible improvement. Lastly, increasing concentrations of Dissolved Organic Carbon (DOC) with distance from the source of the AMD (with the exception of the high concentration at the mouth of the river), may influence metal speciation (Pérez-Esteban et al. 2014).

Community richness nearly doubled at stations furthest from the contamination source in both sampling years, with a maximum of 15 taxa present at the two distant stations (AR7 and DAS). Even our most distant station (DAS), the pH of which is circum-neutral, is influenced by metal contamination from Lake Arnoux (Goulet et al. 2009; Perceval et al. 2006) and its benthic fauna is less rich than that of less-contaminated neighboring lakes (Borgmann et al. 2004).

There was no significant correlation between population densities and distance from the contamination source. For example, the reference station in northern Lake Dasserat (DAS), although taxonomically rich, had low benthic abundances, whereas the station closest to the contamination source had large number of acid-tolerant *Chironomus* larvae prior to site restoration. Thus taxa respond differently to changes in acidity, which does not favor simple correlations between total community abundance and changes in acidity. The lack of a relationship between invertebrate abundances and dissolved trace metal concentrations has been reported previously (Canfield et al. 1994; Malmqvist et al. 1999). As a caveat, we note that within invertebrate groups significant relationships could be obscured by the fact that we did not identify them in detail. For instance, although in our study the abundances of Oligochaeta were not correlated with either distance, pH or metal concentrations, trends in the tolerance of various families of Oligochaeta to metal-contaminated runoff were reported previously (Borgmann et al. 2004; Breneman et al. 2000). Likewise, even sympatric species of the same insect genus can differ widely in their accumulation of trace elements (e.g., *Chironomus*: Martin et al. 2008, Proulx and Hare 2014). Lastly, decreases in acidity and dissolved metal concentrations do not necessarily result in a linear decline in metal concentrations in aquatic invertebrates (Croteau et al. 2002).

Because of the much slower rate of change in sedimentary metal concentrations compared to those in the water column, there is usually a lag between the reduction of metal concentrations in overlying waters and those in pore waters and sediments (Vanbroekhoven et al. 2008). Thus toxicity due to sedimentary metals can continue long after metal concentrations in the overlying water have returned to background levels (Besser et al. 2007). As a consequence, the responses of benthic communities to site restoration are likely to lag behind those of pelagic ones. For example, the recovery rate of stream benthic invertebrate communities from metal-contamination can vary from several months to years (Dsa et al. 2008; Nelson et al. 1996).

The results of our study, suggest that in shallow lakes such as Lake Arnoux the recovery rates of invertebrate communities can be rapid. However, because metal concentrations in sediments have likely been little affected by these short-term changes, benthic communities in the near future are likely to be biased towards taxa that either tolerate metal-contaminated sediments or taxa that are not exposed to these sedimentary contaminants. For example, benthic taxa that irrigate their tubes with overlying water and feed either in the water column or on recently-deposited surface sediments (Hare et al. 2001; Proulx et al. 2014) can persist in the presence of historic metal contamination. In contrast, sensitive taxa that feed on deep sediment could remain absent for decades. The recovery of Lake Arnoux is likely to also depend on whether sediments act as a sink for or a source of dissolved metals (DeNicola et al. 2002). Since the lake is shallow, periods of disturbance could alter redox conditions and return metals to the water column (Devallois et al. 2009; Vanbroekhoven et al. 2008). Disturbances such as this would likely delay the recovery of fish and planktonic communities (García-García et al. 2012).

The biotic indexes exhibited significant improvement after the restoration, with a greater impact for the stations closest to the source of contamination. Overall, trends were observed in spite of the fact that the values of such indexes can be biased by the substitution of sensitive taxa by more tolerant taxa (e.g., Ephemeroptera by Trichoptera) or the presence of taxa that tolerate specific contaminants (Wu et al. 2011). In 2010, the near-absence of Ephemeroptera (only 1 individual at the reference station DAS) and the absence of Odonata and Trichoptera were likely signs of deleterious conditions, the taxonomic richness of both Trichoptera and Ephemeroptera being reported to decrease with increasing metal concentrations (Malmqvist et al. 1999). Taxa such as *Procladius, Glyptotendipes* and *Sialis* appeared only some distance downstream from the contamination source. *Chaoborus* larvae, although abundant in nearby lakes (Croteau et al. 1998) and able to manage metals efficiently in their cells (Rosabal et al. 2012), were present in low densities in Lake Arnoux likely because of the near absence of the planktonic micro-crustaceans on which they feed (unpublished observation). Our results suggest that there was a change in the *Chironomus* community, with the likely substitution of acid-tolerant *Chironomus harpi* by the less acid-tolerant *Chironomus anthracinus* (Proulx et al. 2013). We speculate that the high metal concentrations at this site (Fig. 2) were not deleterious to this taxon because at very low pH (Fig. 3), hydrogen ions tend to outcompete metal ions for uptake sites on aquatic insects, which means that they accumulate little of these potentially toxic metals (Croteau et al. 1998; Hare et al. 2008).

The functional structuration of the communities along the contamination gradient was less apparent than expected. Our results showed a significant impact of pH and several metals on only large individuals, which are apparently more sensitive to low pH and metals than smaller individuals. In addition, despite the fact that the proportions of the four functional feeding groups (gatherer, filterer, shredder and predator) varied with distance and with year, the changes were significant only for gatherers and predators. Indeed, the fact that the station nearest the contamination source was overwhelmingly dominated by gatherers and filterers (*Chironomus, Tanytarsus,* Oligochaeta), likely explained by the high concentrations of iron, and thus precipitated iron oxides, which would likely have smothered periphyton and thus eliminated grazers (Vuori 1995). As stated above, metal toxicity in sediments is likely to persist longer than in the water column (Besser et al. 2007). However, burrowers (principally represented by *Chironomus*) were dominant at the stations close to the mouth of the Arnoux River, which suggests that they either do not consume sediments or that they are tolerant to sedimentary metals. In 2011, predators were found closer to the contamination source (at station AR-2), such that predators, gatherers and filterers were well represented at the 4 stations sampled in 2011. In previous studies, predators were reported to be less sensitive to metal contamination (Liess et al. 2017), and were more abundant in streams affected by AMD, whereas the abundances of filter feeders and gatherers tends to decrease (Hogsden et al. 2012), which is in opposition to our results. The shortage of food resources may explain the absence of predators, and the presence of gatherer and filterers may be more related to the tolerance of the species than their feeding habits. Lastly, in our study, the limited number of replicates may have reduced the power of the analyses, thus obscuring trends in these biological indexes, which are usually useful in the ecological assessment in streams (DeNicola et al. 2016; He et al. 2015). Consequently, negative results cannot be interpreted as a real absence of structuring by some traits along a metals gradient.

In conclusion, only one year after restoration of the abandoned mine tailings there has already been a considerable improvement in the water quality and benthic invertebrate communities of Lake Arnoux, despite the lack of visible functional structuration of the communities along the gradient of contamination. Future changes in water quality, and its influence on benthic communities, will depend in part on the release of metals from sediments as well as the tolerance of various invertebrate species to metals in sediments and the overlying water column.

AUTHOR CONTRIBUTIONS

J. Mocq and L. Hare were both involved in the identification of the individuals, the statistical treatment of the data and the writing of the manuscript.

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