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Environmental changes and macroinvertebrate responses in Patagonian streams (Argentina) to ashfall from the Chaitén Volcano (May 2008)

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ABSTRACT

On May 2nd of 2008 the Chaitén Volcano (Chile, 42°50′S and 72°39′W) erupted explosively producing a strong emission of volcanic ash. As a result of this eruption wide areas on the Argentinean side became covered by ashes. In order to investigate the effects of ashfall on environmental features, water quality and macroinvertebrate communities we conducted a study on 10 rivers affected by ash deposition in their hydrographic basins. Sites were visited seasonally (June 2008–March 2010) and results were compared with data obtained from previous research projects. Measures of pH, conductivity, oxygen content, main nutrients, and total suspended solids (TSS) were taken. Macroinvertebrate samples were obtained from riffles and pools. Community attributes were measured and metrics were calculated. A strong and significant increase in TSS values at most sites was recorded and although the peak diminished rapidly during the following months, resuspension and remobilization of ash continue even 20 months after. No significant changes in pH, conductivity and nutrients, comparing with data previous to the ashfall, were detected. Most rivers showed a strong diminution on macroinvertebrate density and richness, being small rivers more severely affected than the big ones. Correspondence analysis based on abundance data allows distinguishing preeruption from posteruption dates at five rivers. Density data and species richness showed low values in March of 2010, indicating that the community was not completely recovered at some sites. At least 25 taxa resulted significantly and negatively affected. Increased mortality could be related to several factors such as habitat deterioration, food quality diminution, interference with breathing mechanisms and with other physiological and morphological characteristics. Specific-taxa responses on the recolonization process were related to dispersal mechanisms and specific strategies.

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1. Introduction

Volcanic eruptions are major natural disturbances with varied and complex consequences; emissions can include different types of materials being air-borne pyroclastic fragments (*tephra*) the most widespread (del Moral and Grishin, 1999). Explosive volcanic eruptions may impact over a broad range of spatial scales, pyroclastic flows can cover hundreds of km^2 (Annen and Wagner, 2003) but lighter fractions such as ashes can be dispersed more widely affecting thousands of km^2 (Martin et al., 2009). Extensive tephra deposition can lead to significant ecological changes on terrestrial and particularly on aquatic environments (Mc Dowall, 1996). Despite this, very few studies have been fortuitous enough to enable the evaluation of the effects of volcanic eruptions on aquatic communities before and after the event (Collier et al., 2002; Hawkins and Sedell, 1990).

Important changes in physicochemical conditions of the water can occur after an episode of tephra deposition. The concentration of suspended sediments can extremely increase in water bodies having lethal effects on the biota. A report at Toutle River in Mount Saint Helen several months after the main episode in 1980 showed that suspended sediment level still remained extremely high (300 to 1000 mg l^{-1}) (Antos and Zobel, 2005). Ashfall can affect water quality, but can also change the channel geometry and destroy riparian vegetation, as was observed in recent eruptions of volcanoes in Alaska (Dorava and Milner, 1999). Moreover, atmospheric conditions such as rain and snow can remobilize deposited ashes and produce ash-slips several years after the eruption episodes (Bisson et al., 2005). Other important environmental concern is related to water soluble constituents in volcanic ash such as macro- and micro-nutrients, some of them suitable to fertilize continental and ocean ecosystems, but also some trace elements may be toxic (Stewart et al., 2009).

Extensive damage on riparian and aquatic habitats can adversely affect fish and macroinvertebrate communities. Dorava and Milner (1999) observed that in streams blocked with ashfall sediments,

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rapid changes in streambed elevation, extensive flooding and channel migration occurred. Apparently the macroinvertebrate community was recovered 5 years after the ashfall of the most recent eruption of Redoubt Volcano (1989–1990, Alaska).

A pronounced instability of substrates such as shifting beds of volcanic material can play a major role in affecting the macroinvertebrate recolonization process. Concurrently as sediment thickness in river bottom diminishes, substrates stabilize and water quality improves, reestablishing the conditions for colonization (Anderson, 1992). Collier (2002) reported that the flushing of stored sediments during large floods altered habitat structure and increased scouring of periphyton and associated macroinvertebrates downstream during a series of volcanic eruptions (New Zealand). He also observed that short-term deposition of fine volcanic sediments explained the diminution in density of some taxa, although it had little impact on community composition.

Indirect effects after an ashfall episode have been recognized, for example extremely turbid water precludes diatom and algal establishment increasing mortality of grazers by lack of food (Collier, 2002). Sedimentation processes can determine a strong diminution of food quality (del Moral and Grishin, 1999) having consequences on the upper trophic levels. The season or period of ash deposition is crucial to determine the degree of damage and survival (Antos and Zobel, 2005). As observed by Edwards and Sugg (2005) at Mt St Helen the timing of the eruption in early spring favored resident species of arthropods that were still dormant, at the same time the existence of snowbanks in protected areas resulted as important refugees for their survival.

Specific-taxa responses are diverse facing ashfall episodes, for example some ash-avoiding mechanism has been described (Brusven and Horning, 1984; Gersich and Brusven, 1982). Responses seem to be related with life history traits, recolonization mechanisms and dispersal strategies, (Dale et al., 2005; Marske et al., 2007). The persistence of the changes observed in macroinvertebrate communities after an ashfall phenomenon, seems to be related to the intensity and frequency of the disturbance (Resh et al., 1988; Wallace, 1990). Anderson (1992) reported that although over 200 macroinvertebrate taxa were recorded by 1987 after the 1980 megadisturbance event on St Helen, all taxa showed very low densities. Furthermore the post disturbance sequence showed a slow shift in community composition with increases in EPT taxa and decreases in chironomid species.

On May 2nd of 2008 the Chaitén Volcano (Chile 42°50′S and 72°39′W) erupted explosively with a strong emission of volcanic ash. As a result of the prevailing western winds, in few hours this event affected greatly a large area of the northwestern Chubut province (between 42°S and 46°S, Argentina) (Sernageomin, 2008). Ashes, predominantly of rhyolitic composition, covered wide areas ranging from 0.1 to 15 mm of thickness on the Argentinean side (Watt et al., 2009). It was the largest eruption globally since that of the Hudson, Chile, in 1991 (Nillni and Bitschene, 1995) and is considered as the first large eruption of high-silica rhyolite since that of Alaska's Novarupta Volcano in 1912 (Pallister et al., 2010).

Since several projects carried out on the affected area provided us with a comprehensive database of the environmental characteristics and macroinvertebrate communities, this proved to be an excellent opportunity to examine the possible effects of the Chaitén Volcano eruption (Miserendino, 2001; Miserendino and Pizzolon, 2004; Miserendino et al., 2011). We carried out a study from May 2008 to March 2010 on 10 rivers affected by ash deposition and evaluated the impact of ashfall on water quality and macroinvertebrate communities. We hypothesized that higher levels of ash in streams will increase the levels of total suspended solids, in consequence those macroinvertebrate species sensitive to sedimentation will decrease in abundance. We also propose to answer the following three questions: 1 — Which were the main environmental changes in the selected rivers? 2 — How persistent these changes are? 3 — Which groups of macroinvertebrates were the most affected?

2. Material and methods

2.1. Chaitén eruption description and ash characterization

On May 2, 2008, a large eruption began unexpectedly at the inconspicuous Chaitén Volcano in Chile's southern volcanic zone. The Chaitén eruption discharged rhyolite magma, a high-silica composition associated with extremes of eruptive behavior ranging from gentle lava effusion to violent, gas-driven explosions. Ash columns abruptly jetted from the volcano into the stratosphere to an altitude of more than 21 km, followed by lava dome effusion and continuous low-altitude ash plumes (Lara, 2009). Ash plumes continued for about a week, punctuated by two additional stratospheric columns (between 20 and 22 km in altitude) on May 6 and 8 (Carn et al., 2009). According to Watt et al. (2009) nearly $1.6 \cdot 10^{11}$ kg of ash (0.2 km^3 or 160 Mtons) was deposited over 200,000 km^2 of Argentina during the first week of the eruption. By May 12 the total volume of erupted material was estimated to be >2 km^3 (Stewart et al., 2009).

As stated by Ruggieri et al. (2011) and regarding the nature of Chaitén ashes, glass was the main constituent with minor amounts of andesine, quartz and cristobalite. The chemical elements that exhibited higher enrichment factors included As, Cs, Sb, Bi, Th, U, Pb, Cd, Zn and Sr. Some of these elements detected in leachates are potentially toxic and are included in the drinking water guidelines.

2.2. Field methods

Ten rivers were sampled in the present study (Fig. 1). All sites were placed within the area affected by 3 to 10 mm of ashfall as documented by Watt et al. (2009).

In order to compare the effect of volcanic ash on streams we selected our sites taking into account previous studies performed in the area. In the selection process the availability, on a seasonal basis, of environmental and macroinvertebrate information was taken into account. Exceptions were Desaguadero and Rañinto streams, two pristine watercourses located in Los Alerces National Park that were sampled only on April 1996 (Miserendino, 2001). Macroinvertebrate collection was performed with a Surber net in order to obtain quantitative data, and samples were taken by the same operator always using identical procedures as in previous studies. As part of the different macroinvertebrate research projects the Blanco and Rifleros streams were intensively sampled from September 1991 to July 1992 on a monthly basis (Miserendino and Pizzolon, 2004) and during the high and low water periods of 1999–2000 (Velásquez and Miserendino, 2003). Esquel, Nant y Fall, Pipo, Glyn, Cabeza de vaca and Chiquito streams were sampled seasonally (May, September and December of 2005 and February 2006) as part of a project on water quality, biota and land-use (Miserendino et al., 2011). After the episode of May 2nd, all sites were visited in May, June, and October of 2008, February, June and October of 2009 and March of 2010. Due to the fact that a few years had elapsed since the previous studies, those sites in which a land use change or any other possible alterations to the environment could cause high TSS values or produce sedimentation symptoms were avoided when possible. Accordingly, none of the sites revisited experimented major changes in land-use practices before and after the ashfall event. A detailed description of the sites and land uses can be seen in Miserendino et al. (2011).

2.3. Environmental characterization and macroinvertebrate analysis

At each site, percentages of boulder, cobble, gravel, pebble, and sand in the reach were estimated using a 1-m^2 grid. Current speed was measured in mid channel (average of three trials) by timing a float as it

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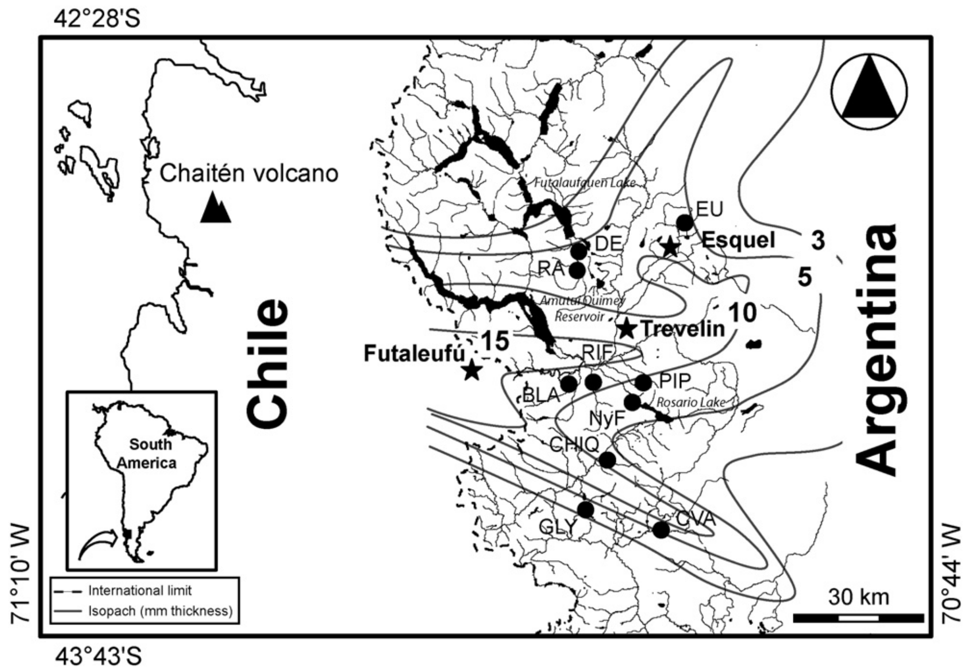

Fig. 1. Map of the study area with location of the 10 sampling sites in Chubut (Argentina) and ash thickness (contours in mm). Site codes are shown in Table 1. Reproduced and adapted from Watt et al. (2009).

moved over a distance of 10 m (Gordon et al., 1994). Average depth was estimated from five measurements with a calibrated stick along one transverse profile across the channel. Wet and dry widths (from bank to bank) of the channel were also determined. Discharge was obtained by combining depth, wet width and current velocity as in Gordon et al. (1994). At each site, air and water temperature were measured with a mercury thermometer.

At each occasion and in the mid channel section of the reach, specific conductance, pH, turbidity and dissolved oxygen were measured with a sensION 156 multiparameter probe. For nutrient analyses water samples were collected below the water surface, kept at 4 °C and transported to the laboratory for analysis. Total suspended solids (TSS) were measured gravimetrically from separate water samples (plastic bottles 2000 ml) taken from the middle of the channel. In the laboratory differences between the final and initial weights of dried filters were obtained. Nitrate plus nitrite nitrogen (NO_3+NO_2), total nitrogen (TN), total phosphorous (TP) and soluble reactive phosphate (SRP) were analyzed using standard methods (APHA, 1994).

Quantitative macroinvertebrate samples were taken with a Surber sampler (0.09 m^2; 250 μm pore size). On each reach, three samples from riffles and three from pools ($n=6$) were taken. Samples were fixed in situ with 4% formaldehyde, and sorted in the laboratory under at least 5× magnification. Macroinvertebrate species were identified to the lowest possible taxonomic level using regional keys (Domínguez and Fernández, 2009; Manzo and Archangelsky, 2008) and counted. To make databases comparable, species lists and matrices were carefully revised and modified when necessary in order to adjust the level of identification of different groups.

We calculated a set of macroinvertebrate community descriptors for each site and sampling date, including richness measures: taxa richness (SR) and Ephemeroptera, Plecoptera and Trichoptera (EPT) richness; enumeration measures: total density (TD) (Barbour et al., 1999; Resh et al., 1995) and diversity measures: Shannon–Weaver diversity index (H′). A biotic index previously adapted for the Patagonian region, BMPS (Biotic Monitoring Patagonian Streams) was calculated (Miserendino and Pizzolón, 1999). The BMPS is an adaptation of the BMWP (Biological Monitoring Working Party index; Armitage et al., 1983) and is obtained from a table of 95 families with different degrees of pollution sensitivity (scores 1–10) present in Patagonia. The total BMPS score ranges from 0 to >150. This index is appropriate to detect the effects of sedimentation processes on biotic communities (Miserendino, 2007).

2.4. Statistical analysis

To establish predictive levels of ash in TSS values a single regression model was performed between ash deposition and total suspended solids. Data employed to the dependent variable (TSS) corresponded to June of 2008. Differences in physicochemical parameters and attributes of macroinvertebrate communities at preeruption and posteruption dates were tested using non parametric ANOVA test (Kruskal–Wallis). The interpretation of this test is basically identical to that of the parametric one-way ANOVA, except that it is based on ranks rather than on means (Sokal and Rohlf, 1995). For pair-wise comparisons we performed Mann–Whitney *U* test which is a nonparametric alternative to the *t*-test for independent samples. The comparison performed included global average from dates before and after the ashfall event on total density, species richness, EPT richness, H′ and BMPS. Abundance of different invertebrate groups such as Plecoptera, Ephemeroptera, Trichoptera, Coleoptera, Oligochaeta and Chironomidae as well as the response of individual taxa before and after the ashfall was also assessed. Single regression models were employed to establish predictive values of TSS on density and species richness. For a better adjustment dependent and independent variables were log transformed. To examine significant changes in community assemblage composition a Correspondence Analysis (CA) on abundance data was performed per studied river, this is an ordination method which assumes unimodal responses in species data (Jongman et al., 1995). Correspondence analysis was chosen because previous inspection of the data revealed a unimodal mode rather than a linear response in the biotic variables (ter Braak and Smilauer, 1998). Matrices on abundance data per taxa including pre and posteruption dates were prepared for all rivers excepting Desaguadero and Rañinto in which only posteruption data were complete. Abundance data were log $(x+1)$ transformed

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Table 1
Environmental characterization of the studied rivers, Chubut, Patagonia, Argentina. Water temperature and flow features are mean values. ($n=6$ for DE, RA, BLA and RIF, $n=10$ for the rest of the sites).

Code name	River	Elevation (m.a.s.l.)	Distance from the source (km)	Distance from the volcano (km)	Area of the basin (km^2)	Slope of the main channel (%)	Stream order	Water temperature (°C)	Width (wet–dry) (m)	Depth (m)	Velocity (m.s^{-1})	Discharge (m^3.s^{-1})
DE	Desaguadero	551	21.2	87.4	65.6	2.99	3	6.57	15.04–22	0.31	1.48	6.44
RA	Rañinto	595	6.3	87.6	13.5	12.21	2	6.07	7.65–15	0.21	1.04	1.64
BLA	Blanco	369	13	94	55.2	8.72	2	8.00	13.80–35	0.29	1.32	5.18
RIF	Rifleros	379	16	98.2	90.5	2.94	3	9.00	8.52–13	0.24	0.83	1.70
EU	Esquel	839	7.7	111.4	22.9	14.25	3	8.10	4.24–10.8	0.18	0.85	0.70
NyF	Nant y Fall	665	21.22	109	161.8	3.88	3	11.72	21.23–31.5	0.28	0.73	4.31
PIP	Pipo	728	2.8	109.6	2.2	9.54	2	9.21	1.38–2.3	0.09	0.26	0.04
GLY	Glyn	615	10.3	112.5	21.7	4.02	2	8.11	3.85–5.7	0.19	0.85	0.83
CHIQ	Chiquito	670	10.7	109.9	11.1	8.67	2	6.75	2.05–3.5	0.14	0.83	0.25
CVA	C. de Vaca	726	24.3	128.9	88.7	1.87	2	7.00	7.76–9.4	0.30	0.85	2.04

prior to the analyses. The CA was run using CANOCO (ter Braak and Smilauer, 1998, 1999).

3. Results

3.1. Environmental effects

A synthesis of the main features of the sites is presented in Table 1. Elevation ranged between 369 and 839 m.a.s.l. whereas distance from the volcano ranged from 87.4 km (Desaguadero) to 128.9 km (Cabeza de vaca). Mean discharge of sites ranged between 0.04 and 6.44 m^3.s^{-1} (Table 1).

Of all the variables measured in the field only TSS evidenced the effect of ashfall in the rivers. Moreover, the predictive value of the ash deposition at the sites (thickness) on TSS values was highly significant in the first post eruption sampling (June of 2008) ($r^2=0.51$, $n=10$, $p<0.02$). A strong increase in TSS values in the water column was detected in May and June of 2008 and in the following months values still remained high (Fig. 2a and b). Increases were 236 times higher at Esquel, 20 times higher at Nant y Fall and Chiquito, and 95 times higher at Glyn, in pair comparisons between May 05 and May 08 (Fig. 2a). In those rivers with data available previous to the episode (Nant y Fall, Pipo, Glyn, Chiquito, Cabeza de vaca) all mean values were higher after than before the ashfall. This difference was significant for Nant y Fall, Glyn and Chiquito streams ($p<0.05$). Although TSS data were not available at preeruption dates for rivers Desaguadero, Rañinto, Blanco and Rifleros, values recorded were high (Fig. 2b). An extreme value of 97.3 mg.l^{-1} of TSS was measured at Blanco River in the next summer after the eruption (Fig. 2b and Table 2). This is a glacier-fed river and melting in

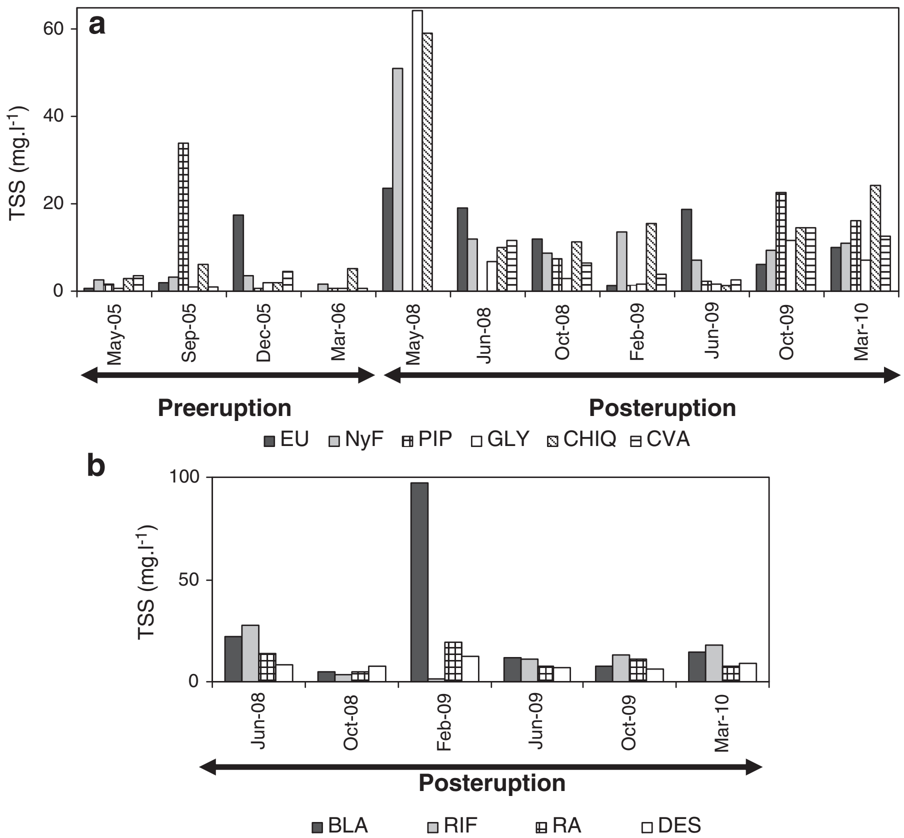

Fig. 2. Total suspended solids (mg.l^{-1}) in the water column on Patagonian rivers after the ashfall of Chaitén Volcano, a) preeruption and posteruption values for rivers: EU: Esquel, NyF: Nant y Fall, GLY: Glyn, CHIQ: Chiquito and CVA: Cabeza de vaca. b) Posteruption values for BLA: Blanco, RIF: Rifleros, RA: Rañinto and DES: Desaguadero.

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Table 2
Physicochemical features of the studied rivers on posteruption dates (all rivers) and preeruption dates (EU, NYF, PIP, GLY, CHIQ, CVA) of the Chaitén Volcano. Data are means, ranges are given in parenthesis. Significance of comparison: in bold: $p<0.005$; underlined $p<0.05$ for Kruskal–Wallis or Mann–Whitney test.

River	*n*	pH	Conductivity (μS. cm^{-1})	Dis. oxygen (mg.l^{-1})	TSS (mg.l^{-1})	*n*	TP (μg.l^{-1})	TN (μg.l^{-1})	*n*	SRP (μg.l^{-1})	NO_3 (μg.l^{-1})
Desaguadero	6	7.01 (6.7–8)	47.2 (40.6–52.7)	12.6 (9.1–15.2)	8.6 (7.1–12.7)	6	14.8	103	6	(<2–3)	(<3–58)
Rañinto		7.33 (6.8–7.9)	44.5 (39.3–53.2)	12.9 (9.2–15.7)	10.7 (4.9–19.5)		10.3	46		<2	<3
Blanco	6	7.45 (6.7–8.4)	33.2 (29.8–38)	12.9 (9.3–15.7)	26.2 (4.5–97.3)	6	14	47	6	<2	(<3–4)
Rifleros		7.64 (6.8–8.4)	70.8 (34.7–107)	12.5 (8.4–16.9)	12.4 (1.2–27.4)		23.6	103		(<2–8)	<3
	Pre/post					Pre/post			Pre/post		
Esquel	4	7.4 (7.2–7.7)	100 (57–139)	11.6 (7.8–15.7)	5.10 (0.7–17.5)	1	4	407	4	<1.5	<2
	7	7.34 (6.6–8.2)	68 (61.2–89.9)	12.9 (9–16.5)	12.98 (1.2–23.6)	7	12.1 (9–20)	48.4 (28–65)	7	(<2–3)	(<3–9)
Nant y Fall	4	7.6 (7.2–7.9)	**14** (112–118)	8.7 (7.7–11.1)	**2.7** (1.7–3.6)	1	8	410	4	<1	<1
	7	7.8 (7–8.6)	**93** (76.3–107.8)	10.5 (7.7–12.7)	**16.1** (7–51.1)	7	19.3 (9–50)	174.8 (130–205)	7	(<2–3)	(<3–7)
Pipo	4	7.3 (7–7.6)	56 (36–69)	12.7 (8.9–18.7)	9.2 (0.6–33.9)	1	13	280	4	<3	<1
	6	7.7 (7.1–8.6)	58 (46.9–71)	9.6 (5.6–11.5)	9.9 (1.5–64.4)	6	33.0 (18–50)	121.8 (93–148)	6	(4–14)	(<3–8)
Glyn	4	7.2 (7–7.3)	<u>77</u> (54–97)	12.4 (9.2–17.6)	<u>1.09</u> (0.7–1.9)	1	2	524	4	<1	<1
	7	7.4 (6.9–7.9)	<u>46</u> (37.6–57.7)	9.3 (6.3–12.3)	<u>13.7</u> (1.5–64.4)	7	25.4 (9–80)	153.6 (85–209)	7	(<2–4)	(4–99)
Chiquito	4	7.2 (6.9–7.4)	50 (9–92)	12.7 (11.9–14)	<u>4.05</u> (2–6.1)	1	26	9	4	<2	<1
	7	7.5 (7–8.1)	55 (46.8–73.2)	10 (6.6–13.7)	<u>19.4</u> (1.3–59.1)	7	42.0 (22–81)	78.3 (66–112)	7	(9–29)	(<3–5)
Cabeza de vaca	4	7.3 (7.1–7.4)	50 (38–63)	11.1 (9.7–12.9)	2.4 (0.7–4.4)	1	13	10	4	<1	<1
	6	7.3 (7.1–7.8)	42 (31.7–66.6)	8.6 (5.3–10.7)	8.7 (2.5–14.6)	6	20.0 (11–32)	100 (85–141)	6	(<2–4)	<3

February probably released the ashes trapped at headwaters. At most sites ash remobilization was frequent even during the second year of study; this can be visualized by comparing values of TSS, those of March 2010 were between 10 and 100 times higher than those of March 2006 (Fig. 2a).

All pH values recorded in the rivers were circumneutral (mean range 7.01–7.8) at both before and after ashfall dates, and differences observed between dates were not significant at all sites ($p>0.05$) (Table 2). As is expected for Patagonian cordilleran rivers conductivity values were low (<139 μS.cm^{-1}). In Nant y Fall and Glyn streams conductivity values were significantly lower after than before the ashfall, but most sites did not show changes in this variable. Dissolved oxygen remained within expected values corresponding to well oxygenated and turbulent mountain rivers. A light increase in PT values at most rivers was observed in dates after the ashfall whereas the TN trend was variable.

3.2. Macroinvertebrate responses

After the ashfall a strong decrease in density data was observed at most studied rivers (Fig. 3), significant differences in density were detected in Esquel, Pipo, Glyn, Chiquito, Cabeza de vaca and Blanco (Kruskal Wallis test, $p<0.05$) (Table 3). However, macroinvertebrate density was not different in preeruption and posteruption dates at Nant y Fall and Rifleros rivers.

Mean taxonomic richness also decreased significantly at posteruption dates at Esquel, Nant y Fall, Pipo, Glyn, Chiquito and Cabeza de vaca (Fig. 4 and Table 3). Global richness showed consistently lower values at posteruption dates in Esquel, Pipo, Chiquito and Cabeza de vaca whereas EPT richness diminished markedly at Esquel, Pipo, and Chiquito. Diversity was significantly lower at Nant y Fall and Chiquito streams at post eruption dates (Table 3).

The BMPS index was lower at 9 of the 10 studied rivers in posteruption dates; however differences were statistically significant only at Pipo, Chiquito and Cabeza de vaca streams.

Although TSS were not available for all rivers at all dates two significant regression models were obtained for the dependent variables density ($r=-0.31$, $p<0.006$, $n=59$) and richness ($r=-0.31$, $p<0.01$, $n=59$), both variables decreased with increases of TSS.

3.3. Community assemblage comparisons

The insect orders Trichoptera, Chironomidae, Plecoptera, Coleoptera and Ephemeroptera showed a significant decrease in abundance at posteruption dates (Table 4). Oligochaeta diminished at Esquel, Nant y Fall and Cabeza de vaca at post eruption dates although a significant increase in density was detected at Rifleros and Chiquito streams.

According to the results of the correspondence analysis some differences on macroinvertebrate community assemblages occurred after the ashfall (Figs. 5 and 6).

At Esquel stream some taxa were only recorded at preeruption dates (e.g. *Neoatopsyche brevispina* (Nb), *Smicridea annulicornis* (Sa) and *Notoperlopsis femina* (Nf), *Brachysetodes* sp. (Br)) (Fig. 5). Other frequent taxa such as *Antarctoperla michaelseni* and *Paratrichocladius* sp. significantly decreased after June 2008 ($p<0.05$, Table 4).

At Nant y Fall the chironomids *Cryptochironomus* sp. (Cry), *Pseudochironomus* sp. (Pseu) and *Pseudosmittia* sp. (Pseud), the oligochaet *Phreodrilidae* sp. (Pheo), the caddisfly *Hudsonema flamini* (Hf) and the stonefly *N. femina* were more common and abundant at preeruption dates (Fig. 5). *Luchoelmis cekalovici*, *Pseudosmittia* sp. and

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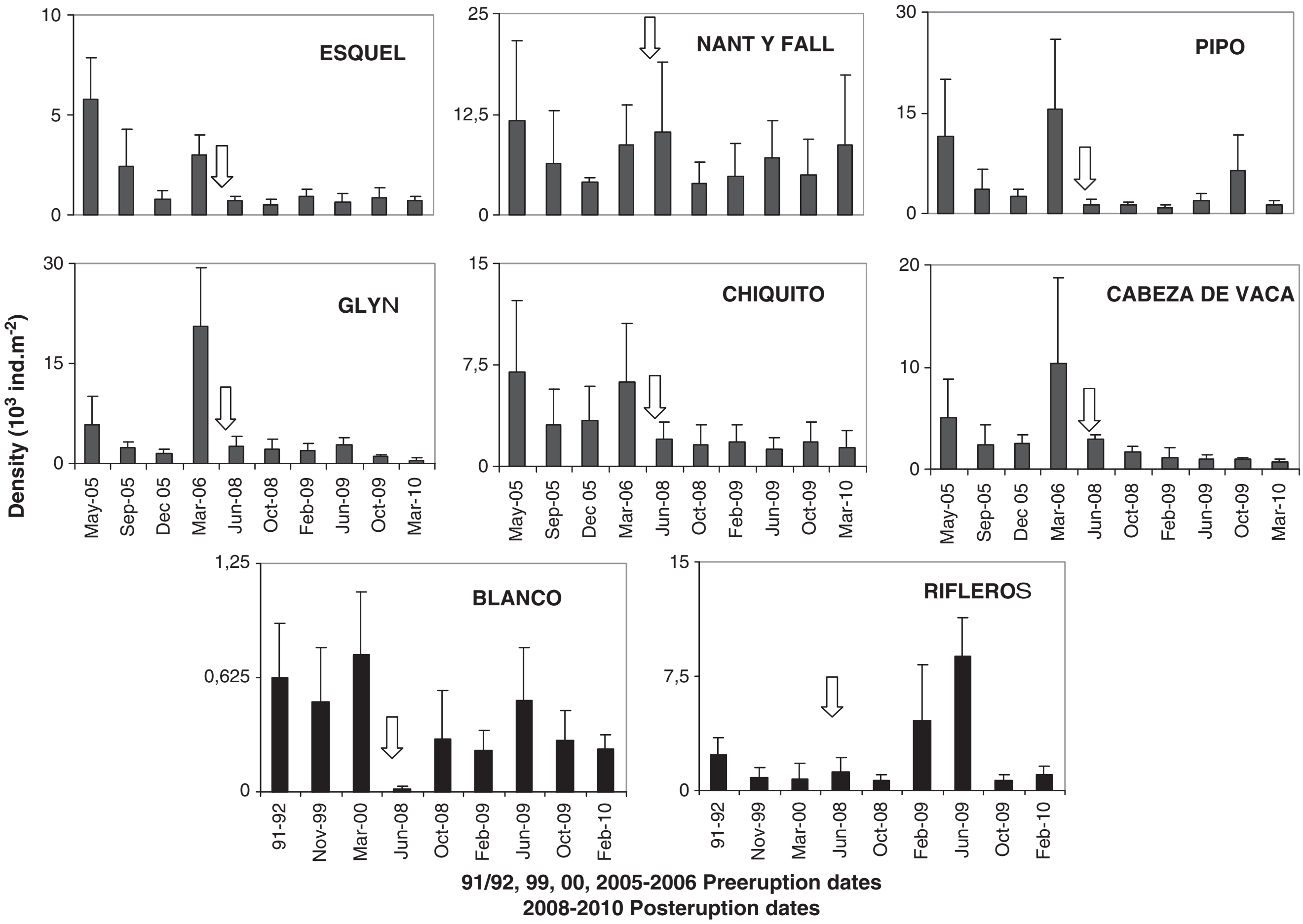

Fig. 3. Mean density of macroinvertebrates (±SD, *n* values in methods) at preeruption and posteruption dates after the ashfall of Chaitén Volcano, at studied rivers in Chubut (Argentina). The arrows point the eruption on May 2nd.

Empididae decreased significantly at post eruption dates (Table 3) (Fig. 5).

Along CA1 a clear separation of dates before and after the ashfall occurred when analyzing Pipo stream. The stoneflies *Austronemoura chilena* (Ac) and *Austronemoura quadrangularis* (Aq), the dipterans, *Podonominae* sp.1 (Pod) and *Podonominae* sp.2 (Podo2), *Cnesia dissimilis* (Cd) and the caddisfly *Mastigoptila longicornuta* (Ml) were well represented at preeruption dates (Fig. 5). Several species of Trichoptera, Diptera and Coleoptera also showed significant differences in density data (Table 4).

Table 3
Summary of benthic invertebrate community indexes associated to the presence and absence of volcanic ash before and after the eruption of Chaitén Volcano in 10 Patagonian rivers. Comparisons are for macroinvertebrate data between samples before and after the eruption from different research projects. BMPS: Biotic Monitoring Patagonian Streams. Significance of comparison is: pairs in bold. $p<0.001$; underline $p<0.05$ for Kruskal–Wallis or Mann–Whitney test. ND: no available for comparison.

River	*n*	Comparison	Invertebrates' density (ind.m^{-2})	Species richness	*n*	Global richness	Shannon diversity	EPT richness	BMPS
Desaguadero	1	Pre-eruption	590		1	21	2.04	11	72
	36	Post-eruption	1095	ND	6	24.6	2.03	11.2	74.6
Rañinto	1	Pre-eruption	175		1	14	1.5	7	75
	36	Post-eruption	431		6	16.4	1.84	8.3	60.7
Blanco	11	Pre-eruption	**623**		11	14.8	1.80	9	75.6
	36	Post-eruption	**299**	ND	6	17.3	1.84	8	64.5
Rifleros	11	Pre-eruption	1299		11	18	2.08	10	88.3
	36	Post-eruption	3111		6	24	2.28	12.8	87.5
Esquel	24	Pre-eruption	**3006**	**16.1**	4	**29.5**	2.29	12.5	90.7
	36	Post-eruption	**730**	**8.7**	6	**19.3**	2.02	8.7	77.2
Nant y Fall	24	Pre-eruption	7709	**24.1**	4	39.2	2.28	18.3	115.2
	36	Post-eruption	6593	**18.7**	6	33.3	1.85	17.2	102
Pipo	24	Pre-eruption	**8273**	**19.9**	4	**34.7**	2.11	**14.5**	**126.2**
	36	Post-eruption	**2162**	**9.3**	6	**21.2**	1.67	**8**	**84.3**
Glyn	24	Pre-eruption	**7566**	**23.2**	4	42.2	2.29	19	123.7
	36	Post-eruption	**1838**	**13.9**	6	29.7	2.07	15.5	96
Chiquito	24	Pre-eruption	**4904**	**25.6**	4	**49.7**	2.60	23.7	**178.2**
	36	Post-eruption	**1635**	**14.9**	6	**34**	2.23	17.5	**129.3**
C de vaca	24	Pre-eruption	**5059**	**21.5**	4	**40.5**	2.54	19.2	107.
	36	Post-eruption	**1389**	**11.7**	6	**27.2**	1.96	12.5	83.8

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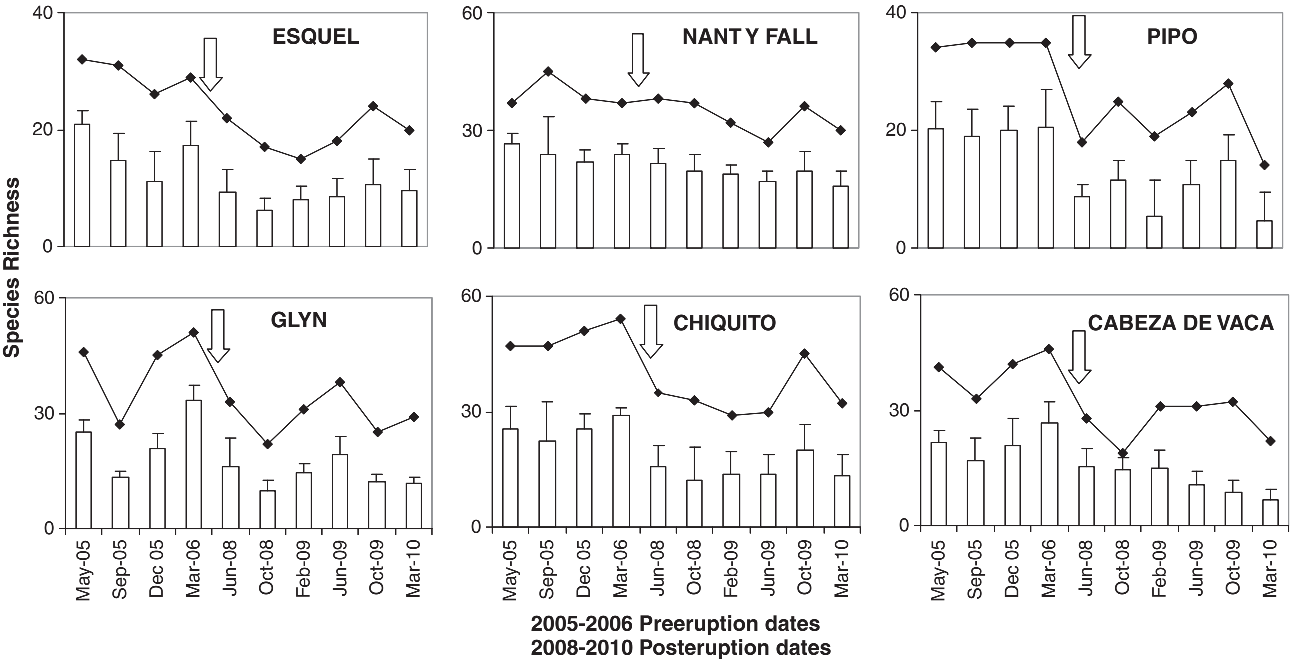

Fig. 4. Mean richness (bars) per sample of macroinvertebrates (±SD, *n* values in methods) and global richness (line), at preeruption and posteruption dates after the ashfall of Chaitén Volcano, at studied rivers in Chubut (Argentina). The arrows point the eruption on May 2nd.

At Glyn stream, there was no clear separation on dates before and after the ashfall, nevertheless the flatworm *Girardia* sp., the elmid *Austrolimnius* sp. and the dipteran *Dasyoma* sp. decreased significantly in abundance at posteruption dates (Table 4).

Although there were no strong differences in benthic assemblages at Chiquito stream (Fig. 5) some taxa diminished consistently after the ashfall (e.g. *Hyalella araucana*, *Brachysetodes quadrifidus*, *Myotrichia murina*, *Austrolimnius* sp.) (Table 4).

A clear distinction between preeruption and posteruption dates can be seen in a CA biplot at Cabeza de vaca (Fig. 5). Most assemblages at preeruption dates corresponded to the well represented taxa (e.g. *Udamocercia arumifera* (Ua), Hydracarina (Hyd), *Nais communis* (Ncom), *Nousia crena* (Nc), *Simulium* sp. (Sim), *Alfonsoperla* sp. (Alf)). Moreover at least 8 taxa including the EPT group and Coleoptera showed a significant decrease in abundance at posteruption dates (Table 4).

At Blanco stream a good distinction between pre and posteruption dates can also be seen in the CA biplot (Fig. 6). Assemblages at preeruption dates were dominated by *Klapopteryx kuscheli* (Kk), *Edwardsina* sp. (Edw), *Senzilloides panguipulli* (Sp), *Simulium* sp. (Sim), *N. femina* (Nf), *Oxyethira bidentata* (Ob), *Cnesia disimilis* (Cd), *Rithroperla rossi* (Rr) and *Araucanioperla* sp. (A). Significant differences in density were also detected for *Meridialaris chiloeensis* and *Brachysetodes* sp. (Table 4).

At Rifleros stream there was not a clear segregation between dates before and after the ashfall (Fig. 5). However, an increase of Oligochaeta was reported at posteruption dates, suggesting that other disturbances, besides the ashfall, could be affecting the macroinvertebrate community.

Although data at preeruption dates were not available for Rañinto and Desaguadero sites, a CA showed some structure in community assemblages. At Rañinto stream samples taken during the first year after the volcano episode were grouped on the right lower quadrant. At Desaguadero samples from June and October (2008, 2009) were grouped, while those collected in the first (February 2009) and second summers (March 2010) were placed separately (Fig. 6).

4. Discussion

After the Chaitén eruption the most evident environmental changes at the studied sites were a strong ash deposition and an increase in suspended solids. In the following months, ash from the river bottom was transported downstream, but an important amount of ash sediment still remained at the riverbanks and pools. Moreover, remobilization of ash through rain and wind from riverine margins, small steeped valleys (Cabeza de vaca, Chiquito, Pipo) or headwater glaciers (Blanco, Rañinto) was also documented at different dates and highlighted in high TSS values. Other concurrent studies in the area reported an important accumulation and remobilization phenomenon among others by wind (Martin et al., 2009; Stewart et al., 2009). This is not surprising since westerly winds are dominant across the region (65% to 75% of the daily observations) and are characterized by high persistence and intensity (mean annual values: 15–22 km.h^{-1}) (Paruelo et al., 1998).

According to our observations, the most marked impact on macroinvertebrates was a significant diminution in density and richness at most sites in the 22-month study period. These results are generally in line with observations of rivers disturbed by moderate to high volcanic ash depositions in other regions of the world (Anderson, 1992; Collier et al., 2002; Dorava and Milner, 1999) and also with rivers affected by siltation processes as a consequence of anthropogenic activities such as dredging, road construction or deforestation practices (Harding et al., 2001; Wantzen, 1998; Ryan, 1991). Our findings suggest that possibly the ashfall impact on the benthic community was more dramatic in small rivers than in larger ones, characterized by a greater discharge (Death et al., 2003). In addition there were several catchment attributes that surely influenced on how the ash was distributed and transported at each drainage basin, for example surface area, mean height and slope of the main channel (Coronato and del Valle, 1988). The richness diminution was over 40% at small to medium size rivers such as Esquel, Pipo, Glyn, Chiquito and Cabeza de vaca, whereas at Nant y Fall richness diminution was at 22%. It is possible that the presence of Rosario Lake upstream of Nant y Fall River could reduce the impact of the ash by trapping sediments and buffering the scouring effect of flow.

Flow rates determine the rate and mechanisms of store, distribution and transport of fine sediment on the riverbed (Harrison et al., 2007). As a result of low discharge and slow water velocities it was evident that Pipo stream failed in mobilizing sediments downstream. This

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Table 4
Summary of benthic invertebrate taxa and faunistic groups having significant differences in abundance between preeruption dates and posteruption dates (Chaitén Volcano) in a site according to Mann Whitney test pair comparisons or Krukal–Wallis. Significance is given *p<0.05; **p<0.005. All trends detected are decreases in abundance except for those marked as (+). FFG: functional feeding group. P: predator, Sh; shredder, SG: scraper–grazer, CF: collector–filterer, CG: collector–gatherer.

Taxa	FFG	Code	*n* pre	post	River
Turbellaria					
Girardia sp.	P	*Gir*	4	6	GLY**
Oligochaeta spp.			4	6	(+) RI**
			24	36	EU** NyF**CVA** (+) CHI**
Amphipoda					
Hyalella araucana	CG	*Hy*	4	6	CHI**
Plecoptera			24	36	EU**PIP*GLY**CHI**
Antarctoperla michaelseni	Sh	*Am*	4	6	EU*CVA**
Klapopteryx kuscheli	Sh	*Kk*	4	6	BLA**
Ephemeroptera			24	36	EU* PIP*CVA**
			10	6	BLA**
Andesiops ardua	SG	*Aa*	4	6	CVA*
Meridialaris chiloeensis	SG	*Mchi*	4	6	PIP*BLA**
Trichoptera			24	36	EU*NyF*PIP**GLY**CVA**CHI**
			10	6	BLA*
Hudsonema flamini	Sh	*Hf*	4	6	CVA**
Brachysetodes sp.	Sh	*Bra*	4	6	PIP**BLA*
Brachysetodes quadrifidus	Sh	*Bq*	4	6	CHI**
Myotrichia murina	Sh	*Mm*	4	6	CHI**PIP*
Parasericostoma ovale	Sh	*Po*	4	6	CVA**
Neopsilochorema tricarinatum	P	*Nt*	4	6	PIP**
Rheochorema lobuliferum	P	*Rl*	4	6	PIP*
Coleoptera			24	36	NyF**PIP**GLY*CHI**
Luchoelmis cekalovici	SG	*Lck*	4	6	CVA*NyF*PIP**
Luchoelmis sp.	SG	*Lu*	4	6	CVA**
Austrolimnius sp.	SG	*Aus*	4	6	CHI*GLY*
Diptera Chironomidae			24	36	EU**NyF**PIP**CVA**CHI**
Pseudosmittia sp.	CG	*Pseud*	4	6	NyF*
Lopescladius sp.	CG	*Lop*	4	6	CVA**PIP**
Thienemanniella sp.	CG	*Thie*	4	6	CVA**CHI*
Paratrichocladius sp.	CG	*Par*	4	6	EU*
Empididae sp.	P	*Emp*	4	6	EU**NyF**
Ceratopogonidae sp2.	P	*Cer2*	4	6	EU**PIP*
Dasyoma sp.	P	*Dasy*	4	6	GLY*
Simulium sp.	GF	*Sim*	4	6	BLA*
Edwardsina sp.	SG	*Edw*	4	6	BLA*

small watercourse is a clear example of how sedimentation episodes, in this case produced by volcanic ash, strongly affect the invertebrate community. The assemblages between pre and posteruption dates were markedly different as was revealed in the correspondence analysis. On the other hand, Cabeza de vaca was the most distant studied site from the volcano, however a great part of the upper basin showed at least 10 mm of ash deposition (Fig. 1). This might explain the effect on invertebrate taxa composition before and after the ashfall, thus the high sediment loads in the upper sections of the river possibly altered recolonization sequences downstream.

Ash deposition also determined changes in community composition and specific taxa responses. A total of 25 taxa were temporarily extirpated and did not reappear or recover in density by the last sampling dates of the study (almost 2 years after the eruption). Trichoptera was the insect order with a higher number of affected taxa; at least 7 species being significantly and negatively impacted were recognized. Anderson (1992) found that the establishment or survival of Trichoptera larvae was the limiting factor, rather than the failure of adults to arrive to a site affected by volcanic ash. On the other hand, *Brachysetodes* sp. and *B. quadrifidus* (sand case-bearing) could be particularly prone to burial. Dobson et al. (2000) observed that sand-cased caddisfly larvae settled out of drift more rapidly than non case-bearing organisms after siltation.

In general, the ash impact was severe for species of Trichoptera, Coleoptera, Chironomidae, Plecoptera and Ephemeroptera. Several causes can lead to direct or indirect insect mortality. The most obvious is the burial of organisms due to the falling of large amounts of ash; this can be exemplified by the numerous cases of insect fossils found in ash-based sediments such as lacustrine and freshwater deposits. Some volcanic events are known for producing large ash dumps, resulting in an instantaneous insect mortality (Beattie, 2007). Considering that many species of Chironomidae are deposit feeders and pool inhabitants it was not surprising that the group resulted negatively and significantly affected by ashfall at five of the studied rivers. However, after Mt Saint Helen's episode, chironomids were the dominant taxa in recovery sequences at Clear Water Creek and other streams and water bodies near Spirit Lake (Anderson and Wisseman, 1987; Edwards and Suggs, 2005). Massaferro and Corley (1998) documented a complete absence of chironomid fauna within tephra layers and a rapid recovery of diversity and equitability to a predisturbance level in sediments at Mascardi Lake (Patagonia, Argentina). Similarly, Urrutia et al. (2007) reported changes in chironomid assemblages in response to a recent volcanic event in Lake Galletue (Chilean Andes).

The significant diminution of the grazers *Andesiops ardua* and *M. chiloeensis* (mayflies) was probably a response to a decrease of algae and the scouring effects of the flow, which is similar to what was observed by Collier (2002) for *Deleatidium* sp. in the Tongariro River after the Ruapehu eruption. According to Harrison et al. (2007) members of EPT group are particularly vulnerable to sedimentation because they inhibit periphyton growth, diminish prey density, and reduce available oxygen and interstitial spaces for refuge. Other taxa that resulted affected were *L. cekalovici*, *Luchoelmis* sp. and *Austrolimnius* sp. (Elmidae), these taxa were vulnerable to sedimentation in the Chubut river, a large arid Patagonian river (Miserendino and Archangelsky, 2006). Since adult elmids breathe by means of a plastron it is probable that the siltation process affects the breathing mechanism by blocking or obstructing this physical gill.

Other important cause of insect mortality is the abrasion of the cuticle, essentially of the cement and wax layers of the epicuticle or envelope, the outermost layer of the cuticle (Klowden, 2007). The cuticle is extremely important to protect terrestrial insects from desiccation, and volcanic ash acts as a physical insecticide (Brown and Hussain, 1981; Edwards and Schwartz, 1981). In the case of aquatic insects, the cuticle is responsible for maintaining a proper water and ion balance between the inner and the freshwater media (osmoregulation) (Ward, 1992; Williams and Feltmate, 1992). Therefore the abrasive action of the ash can result in a constant influx of water and an outflow of ions, producing a physiological imbalance and a possible death of the organism. The ash can also interfere with gill and plastron respiration of both adult and larval stages in insects. Other known effects are: 1 — spiracular occlusion, probably not important in aquatic species since most aquatic species that breathe through their spiracles usually have them protected by different structures (hairs, elytra, etc.); 2 — excess of salivation, also not important in aquatic insects since water is not a limiting resource; 3 — interference with the digestive processes by the ingestion of the ash, this affects both terrestrial and aquatic species; 4 — abrasion of the mandibles and mouthparts, this can also affect both terrestrial and aquatic species (Collier, 2002; del Moral and Grishin, 1999; Edwards and Schwartz, 1981; Harrison et al., 2007; Marske et al., 2007; Wiederholm, 1984).

Species having a short life-cycle (midges) seem to be better colonizers than long life-cycle species (stoneflies) after ashfall episodes, as reported in the Mangaturuturu River after an acidic *lahar* (a volcanic mudflow) (Collier et al., 2002). According to these authors although several invertebrate species were able to reach the stream, the only ones that flourished were those able to complete their life-cycle between flushes of volcanic ash and debris during snowmelt. However, we did not observe a consistent pattern related with long

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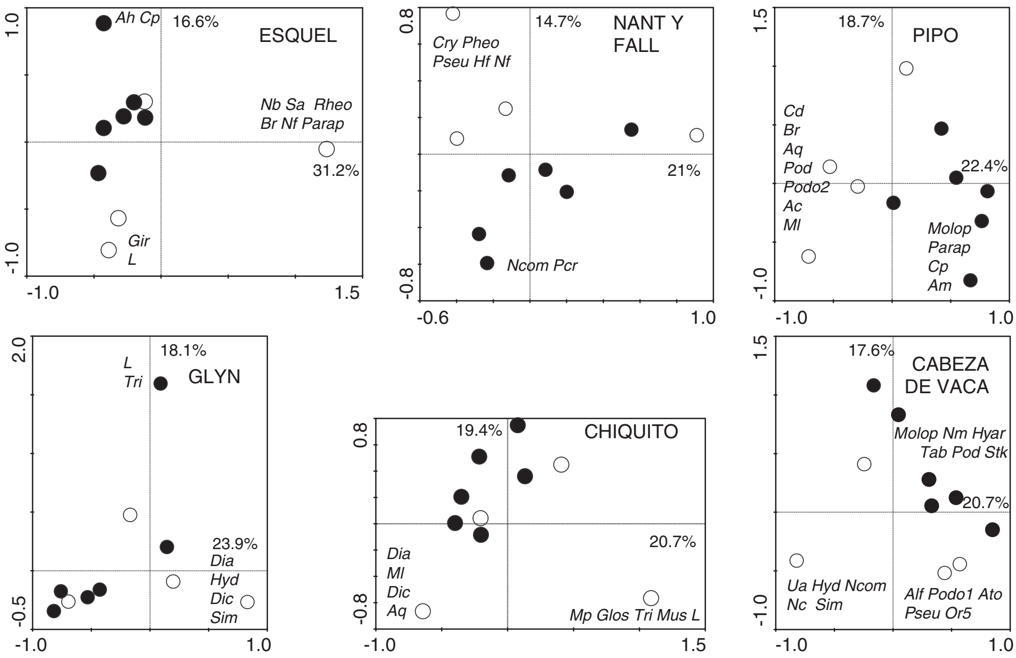

Fig. 5. Correspondence analysis for invertebrate assemblages on the studied rivers, number of macroinvertebrate taxa considered in each river are: EU: 42, NyF: 76, PIP: 68, GLY: 77, CHI: 96, and CVA: 80. Open circles: preeruption dates, black circles: posteruption dates. Taxa with the highest loadings on each axis are shown. Taxa codes are shown in Table 4 and text. Horizontal axis is CA1, vertical axis is CA2.

or short life cycle features in recovery sequences after the volcano impact. The phenomenon affected semivoltine taxa (*K. kuscheli*), univoltine species (e.g. *A. michaelseni*, *A. ardua*, *B. quadrifidus*), bivoltine ones (*M. chiloeensis*) (Brand and Miserendino, 2011a, 2011b; Epele et al., 2011; Hollmann and Miserendino, 2006, 2008) and probably multivoltine species (*Pseudosmittia* sp., *Lopescladius* sp., *Paratrichocladius* sp.). Since many of the aquatic species of insects in the area display univoltine life cycles (Brand and Miserendino, 2011a, 2011b) we consider that the recolonization sequence should take between 6 months and 2 years. As suggested by Dorava and Milner (1999) where drift is present recovery tends to be more rapid than when recolonization has to rely on aerial sources. However, we suspect that the successful larval establishment by drifting was strongly linked with absences of pulses of suspended sediments. Chaitén ashfall could be considered as a megadisturbance event comparing to other episodes such as the short-term deposition reported by Collier (2002), which apparently had little impact on community composition. As we see, being the affected area so broad, the recolonization by flying adults should occur from undisturbed catchments or non-impacted or protected places. As stated by Hawkins and Sedell (1990) certainly refugia play a crucial role after disturbances in the recolonization sequences.

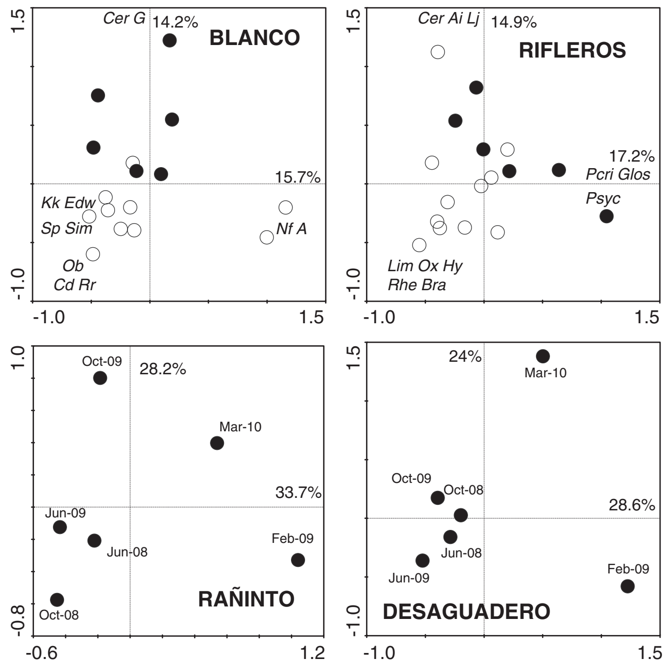

Fig. 6. Correspondence analysis for invertebrate assemblages on the studied rivers, number of macroinvertebrate taxa considered in each river are: BLA: 42, RIF: 47, RA: 40 and DES: 53. Open circles: preeruption dates, black circles: posteruption dates. Taxa with the highest loadings on each axis are shown at Blanco and Rifleros. Taxa codes are shown in Table 4 and text. Horizontal axis is CA1, vertical axis is CA2. Numbers indicate percentage of variance associated with axes.

From all the studied rivers Rañinto and Blanco sustained the lowest richness; these glacier-fed rivers where siltation is a common phenomenon are naturally poor in species. Glacier-fed environments are frequently turbid and are probably inhabited by a siltation resilient fauna (Brown et al., 2007; Milner et al., 2001; Dorava and Milner, 1999; Ward, 1994). Indeed, at Blanco a significant decrease in density but not in richness was documented, unfortunately the absence of preeruption data at Rañinto prevents further comparisons. A large amount of ash was delivered to Blanco River as consequence of melting of the headwater glaciers during February 2009. A similar event was observed in Ape Glacier which was affected by ashfall from Saint Helens during the late summer, having consequences on the stream biota resulting from the scouring and smothering by fine sediments (Anderson, 1992). These subsequent ash delivery episodes probably diminished the rate of the recolonization process at our glacier-fed rivers such as the Rañinto and Blanco in which the diminution of EPT richness beyond February 2009 was remarkable.

5. Conclusion

Fine sediment accumulation is widely acknowledged as a major cause of degradation of the ecological condition of rivers (Wallace,

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1990); however this kind of disturbance at broad regional scales has been poorly examined (Harrison et al., 2007). As in other studies analyzing the impact of sediment deposition on benthic communities, in this paper we linked the ashfall event with an important invertebrate mortality and compositional changes. According to the literature, the recovery process of benthic communities after ashfall episodes took more than 10 years at St Helen (Anderson, 1992), 5 years at Redoubt (Dorava and Milner, 1999), and several years at Mt Ruapehu (Collier et al., 2002). Considering that the 2008 ashfall episode of Chaitén was probably the first one in 9400 years (Naranjo and Stern, 2004) this event was at least unexpected (Carn et al., 2009). Our conclusions are that at some of the studied rivers affected by Chaitén ashfall the recovery process is still occurring, given the magnitude of the event and because the delivery of ash was faster, benthic communities at big rivers were probably less affected than the small ones. However in those medium size rivers having high sediment accumulation upstream the effects on invertebrates were also persistent. This paper will contribute to a better understanding of the disturbance phenomena on aquatic environments related with sedimentation processes resulting from natural causes (Puyehue eruption Chile, June 2011); nevertheless we consider that our results can be equally extrapolated to those sedimentation phenomena produced by anthropogenic causes.

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