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1 **Environmental and spatial factors drive diatom species distribution in Alpine streams:**
2 **implications for biomonitoring**

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8

9 **ABSTRACT**

10 Given their documented capacity to track changes in environmental conditions and human alterations,
11 benthic diatom communities are at present widely used in biomonitoring programs to evaluate stream
12 water quality. However, it is becoming more and more evident that species ecological preferences are
13 not the only drivers of diatom community composition, since dispersal-related processes also play a
14 role. This is particularly compelling in Alpine streams, where orographic conformation and human-
15 related impacts limit dispersal of organisms. In addition, several environmental variables may
16 influence diatom community in pristine or impacted sites. We here investigate the differential role of
17 environmental and spatial factors in driving the community assemblages of diatoms in streams of the
18 Eastern Italian Alps, focusing on both taxonomic and functional composition. We analysed data from
19 110 samples collected on two different geological substrates, i.e. calcareous and siliceous, during the
20 last eight years of biomonitoring programs, among which 64 collected in reference sites and 46 in
21 impacted sites. We first evaluated whether diatom communities in reference and impacted sites are
22 differentially shaped by environmental and spatial factors, highlighting the major role of spatial
23 constraints in both of them. In particular, anthropogenic disruption of longitudinal connectivity in
24 streams likely shaped impacted communities, as demonstrated by the increasing abundance of motile

25 taxa, which are associated with physical disturbance. Conversely, reference communities were mostly
26 affected by spatially structured environmental variables, especially those related to streambed
27 lithology. We then compared the taxonomic and functional composition of diatom communities
28 between the two geological substrates in both reference and impacted sites to better highlight the
29 differential role of this factor. Our results demonstrate that lithology strongly drives diatom
30 community composition in reference but not in impacted sites, confirming our previous observations.
31 The analysis of functional traits, however, highlighted how differences were due not only to the
32 geological substrates, but also to other environmental variables, like flow velocity. Overall, the effect
33 of the spatial component on the structure of diatom assemblages can represent a background noise in
34 the framework of the river quality assessment, and this should be taken into account especially in
35 those countries, like Italy, covering a broad range of mountain areas.

36 **Key-words:** reference sites, ecological guilds, functional groups, dispersal limitation, variation
37 partitioning

38

39 **Highlights**

- 40 • Diatoms track changes in environmental conditions and human alterations
- 41 • Dispersal is expected to affect diatom distribution in Alpine streams
- 42 • Substrate lithology affects diatom community in reference sites
- 43 • Chemical variables and spatial processes affect diatom community in impacted sites
- 44 • Biomonitoring programs should account for the combined effects of spatial and
45 environmental processes

46 **1. INTRODUCTION**

47 Given their documented capacity to track changes in environmental conditions and human alterations,
48 diatoms have been gradually included in all the European monitoring programs as biological
49 indicators for the quality assessment of lotic freshwater ecosystems, after the publication of the
50 Waterframe Directive (2000/60/CE). Diatom responses to environmental variables acting at multiple
51 scales of analysis have been widely documented in literature (Rimet et al., 2004; 2007; 2009; Tison
52 et al., 2005; Grenier et al., 2006; Bona et al., 2007; Soininen, 2007). For instance, Soininen (2007)
53 identified flow velocity and substratum composition as key determinants of diatom composition at
54 local scale, whereas ion concentrations and trophic conditions mainly drive changes in river diatom
55 communities at a regional scale (Bona et al., 2007; Soininen, 2007). However, it has been recently
56 proved that species ecological preferences alone are not sufficient to explain diatom community
57 composition, since dispersal processes also play an important role in shaping communities (Heino,
58 2013).

59 Owing to their physical, topographic and climatic heterogeneity, Alpine streams are extremely
60 heterogeneous, encompassing large variation in environmental variables, like flow velocity,
61 temperature and ion concentrations, over short distances (Ward, 1994). This environmental
62 heterogeneity likely exerts a selective pressure on organisms inhabiting Alpine lotic freshwater
63 ecosystems, which track their optimal environmental conditions according to their ecological niche.
64 In Alpine streams, where ion and nutrient concentrations are usually very low, geology and, as a
65 consequence, conductivity and hardness resulted among the most important factors in shaping diatom
66 communities (Rimet et al., 2004; 2007; 2009; Tison et al., 2005; Grenier et al., 2006), but also altitude,
67 dissolved oxygen, nitrate, calcium, turbidity and pH are among the main environmental factors
68 shaping diatom assemblages in such oligotrophic ecosystems (see Falasco et al., 2012 for an example
69 in Western Alps and Cantonati, 1998; Cantonati et al., 2001; 2006; 2007; 2009; Beltrami et al. 2012
70 for examples in the Eastern Alps). However, recent works have highlighted that the expected

71 responses of diatoms to environmental parameters are not completely fulfilled, especially in mountain
72 streams, due to the effect of spatial processes (Bottin et al., 2014; Dong et al., 2016).

73 Although composition of diatom communities is clearly shaped by environmental variables and
74 habitat heterogeneity at local scale (i.e. species sorting), the role of spatial factors should be kept into
75 account at regional/global scale (Soininen, 2007; Verleyen et al., 2009). The importance of diatom
76 dispersal-related processes in the framework of the biological monitoring has been recently proved
77 in lacustrine ecosystems (Vilmi et al., 2016). Although lake communities are more spatially-
78 structured than stream ones, due to the higher dispersal limitation characterizing the lentic species
79 (Soininen, 2007; Marquardt et al., 2017), Bottin et al. (2014) remarked the importance of the spatial
80 component also in mountain streams, where steep slopes surrounding streams might limit organism
81 dispersion (Dong et al., 2016). In addition, also human alterations such as stream channelization, flow
82 regulations and the construction of reservoirs, interrupt habitat connectivity and limit dispersal of
83 organisms. For instance, water scarcity, caused by both local impacts and global changes, has recently
84 become the most critical threat for diatom lotic assemblages in mountain streams, altering the
85 taxonomical and functional composition of benthic communities ((Bona et al., 2008; Falasco et al.,
86 2018; Piano et al., 2019). Thus, anthropogenic impacts in Alpine streams are expected to alter not
87 only chemical variables but also the spatial processes underlying the composition of diatom
88 communities, overriding the role of natural environmental filters or physical barriers (such as
89 lithological substrates and orographic barriers). A better understanding of the role of environmental
90 and dispersal-related processes in shaping diatom communities is then compelling to enhance the
91 implementation of diatom-based biomonitoring programs in Alpine streams.

92 One of the main outcomes of anthropogenic disturbance on the composition of biotic communities is
93 biotic homogenization, which is defined as an increase in the similarity of species composition (Olden
94 et al., 2004). Environmental filters and dispersal barriers caused by the human activities likely cause
95 the loss of rare and specialised species, and the gain of widespread tolerant ones, with consequent

96 biotic homogenization. In addition, according to the “habitat templet theory” (Southwood, 1977,
97 1988; Townsend and Hildrew, 1994), the above mentioned selection processes may have major
98 effects on particular functional traits, like morphological or physiological attributes, or they could
99 affect the realized niche of a certain species (Webb et al., 2010), causing also functional
100 homogenization (Olden et al., 2004). Thus, the investigation of these processes may provide
101 information on the effects of anthropogenic pressures on biotic communities.

102 According to Leibold and Chase (2017), the relationship between taxonomic and functional
103 homogenization allows us to infer which processes are acting: while taxonomic homogenization
104 underlies dispersal limitation, functional homogenization is a signal of environmental filtering. In
105 particular, anthropogenic environmental filters and spatial barriers are expected to differentially affect
106 species within the original communities based on their functional traits. Therefore, exploring shifts
107 in the functional profile of a community could shed light into mechanisms underlying community
108 assemblages (Leibold and Chase, 2017).

109 We here analysed the community composition of diatoms in streams of the Eastern Italian Alps
110 (Trento province), by collating a dataset of data collected during eight years of biomonitoring
111 programs (2008-2016). In particular, we aimed at: i) investigating the differential role of
112 environmental variables and spatial factors in driving the community composition in pristine and
113 impacted sites within Alpine streams; and ii) unravelling whether taxonomic and/or functional
114 homogenization occur in pristine and impacted sites and whether the lithological substrate may drive
115 these processes. We hypothesized that: i) diatom composition in pristine sites would be mainly shaped
116 by spatial factors, because the variation in chemical parameters within these oligotrophic ecosystems
117 is expected to be low; conversely, chemical parameters would have a determinant role in impacted
118 sites; ii) functional homogenization would occur in impacted sites as a consequence of environmental
119 filters; and iii) lithological substrate would cause taxonomic differentiation in pristine sites, where
120 species can track their ecological preferences without constraints of chemical variables (Rimet et al.,

121 2004; 2007; 2009; Tison et al., 2005; Grenier et al., 2006), but not in impacted sites, where chemical
122 parameters are the main drivers of diatom community composition.

123

124 **MATERIALS AND METHODS**

125 **1.1. Study area**

126 The Trento province is located in the North-East of Italy and covers an area of nearly 6000 km².
127 Within this area, two hydrocoregions (hereafter HERs), i.e. homogeneous areas in terms of geology,
128 altitude and climate (Wasson et al., 2002), were defined consistently with WFD requirements. Both
129 HERs are Alpine and, within each HER, reference sites with potentially homogeneous, pristine
130 environmental conditions and unaltered diatom communities were identified (Rimet et al., 2004). The
131 first HER (hereafter calcareous HER), is the Southern Pre-Alps and Dolomites hydrocoregion,
132 characterized by mountain streams flowing on calcareous substrate (massive and carbonated rocks).
133 The second HER (hereafter siliceous HER) is the Inner Alps hydrocoregion, with high mountains
134 and streams flowing on siliceous substrates (crystalline rocks). Diatom biomonitoring in streams has
135 been carried out by the Environment Protection Agency of Trento province (APPA TN) since 2004.
136 The monitoring network, including 166 sites in the entire Trento province, was designed to provide
137 a coherent and comprehensive overview of ecological and chemical status within each river. In
138 accordance with the monitoring program, every site is sampled twice in a year every six years (every
139 three years for reference sites), considering biological, hydromorphological and physico-chemical
140 quality elements, and pollutants discharged into the river basin or sub-basin.

141 In this study area, we analysed diatom communities collected from both HERs, in 17 reference and
142 16 impacted sites (Table 1), during the last eight years of biomonitoring programs (2008-2016). 11
143 reference sites were selected following the official national criteria (DM 56, 14/04/2009), i.e. sites
144 characterized by null or slight human impacts, unaltered hydrological conditions, intact three-
145 dimensional river connections, null or slight hydromorphological modifications, high water quality,

146 and biological communities showing taxonomical composition and densities corresponding to the
147 unaltered conditions. Beside these official stations, 6 further sites with minor hydromorphological
148 alterations were considered similar to reference sites because of their high water quality and were
149 added to reference category for this study. Impacted sites are located in water bodies characterized
150 by agricultural and urban pressures and they have high nutrient concentration and pesticide
151 contamination (Fig. 1).

152 **1.2. Physical and chemical analyses**

153 Water samples for the physical and chemical analyses were collected along with diatom sampling. In
154 both reference and impacted sites we analysed the following 15 parameters using standard methods
155 (see Table 2): Biological Oxygen Demand (BOD₅), carbonate hardness (HARD), Chemical Oxygen
156 Demand (COD), Chlorides (Cl⁻), conductivity (COND), dissolved oxygen (DO), nitrates (N-NO₃),
157 orthophosphates (P-PO₄), sulphates (SO₄), temperature (TEMP), pH, total nitrogen (N_{tot}), total
158 phosphorous (P_{tot}), total suspended sediments (TSS), turbidity (TURB).

159 **1.3. Diatom collection and treatment**

160 In total, we collected 64 diatom samples from 17 reference sites and 46 diatom samples from 16
161 impacted sites (see Tab. 1 for details).

162 Samplings were performed between 2008 and 2016. Following the WFD requirements, each site
163 belonging to surveillance monitoring was sampled at least twice during the 8 years monitoring
164 program (mainly in spring and autumn). Some sites (Table A1), belonging to core network
165 monitoring, were sampled in three different years (2 samples per year X 3 years = 6 samples).
166 Epilithic diatoms were collected following the standard procedure (European Committee for
167 Standardization, 2003). In each site, we chose 5 cobbles from the main flow and we collected
168 periphyton by scraping their upper surface by means of a toothbrush. Samples were than preserved
169 in ethanol and moved in laboratory for the treatment with H₂O₂ (30%) and HCl (European Committee

170 for Standardization, 2003). Slides for the observation at the light microscope were mounted by means
171 of Naphrax®. Diatom identification was based on several diatom floras and monographies, as well
172 as recent taxonomic papers (Krammer and Lange-Bertalot, 1986-1991 a, b; Lange-Bertalot and
173 Metzeltin, 1996; Krammer, 1997 a, b; 2002; 2003; Reichardt, 1999; Lange-Bertalot, 2001; Werum
174 and Lange-Bertalot, 2004; Blanco et al., 2010; Hofmann et al. 2011; Bey and Ector, 2013; Falasco et
175 al., 2013; Ector et al., 2015). We identified at least 400 valves in each sample. Diatom communities
176 were analysed in terms of biodiversity, taxonomical composition, ecological guilds and growth forms
177 (Rimet and Bouchez, 2012).

178 **1.4. Statistical analyses**

179 All statistical analyses were performed with the software R 3.4.2 (R Development Core Team, 2017).

180 *1.4.1. Characterization of environmental features and diatom community*

181 We performed the Mann-Whitney U-test to check for differences in environmental variables between
182 references and impacted sites on the whole dataset and between the two HERs within the reference
183 and impacted datasets. To highlight statistically significant species, representative of the two
184 hydroecoregions for both reference and impacted sites, we performed an Indicator Species Analysis
185 (Dufrière and Legendre, 1997) with the function “multipatt” in the package *indicspecies* (Caceres and
186 Legendre, 2009).

187 *1.4.2. Environmental parameters vs spatial processes*

188 To test whether diatom communities in pristine sites are more shaped by spatial factors than in
189 disturbed sites (Hypothesis 1), we investigated the role of environmental vs spatial parameters in both
190 reference and impacted sites. To achieve this aim, we performed a partial-RDA, following the
191 approach suggested in Peres-Neto et al. (2006) and De Bie et al. (2012). Using redundancy analysis
192 (RDA), we built up two explanatory matrices: a chemical matrix [C], including all chemical
193 parameters, and a spatial matrix [S] with both the coordinates of the sampling sites and the spatial
194 variables extracted by Moran’s Eigenvector Maps analysis (MEM, see Dray et al., 2006). The MEM

195 analysis partition the spatial information into variables representing the potential autocorrelation
196 between spatial points at different scales. With this procedure we generated a set of orthogonal, and
197 thus non-collinear, spatial variables that are derived from geographical coordinates of the study sites,
198 each of which corresponds to a specific spatial structure and scale. These variables can model coarse
199 patterns in the community data and then progressively represent finer-scale patterns (Borcard et al.,
200 2004). Both chemical and spatial variables were selected by means of a forward selection performed
201 with the R package *packfor* (Dray et al., 2013) to obtain a parsimonious combination of variables, i.e.
202 including only variables with a significant relationship with the community matrix. We separately
203 tested the [C] and [S] matrices against the taxonomic matrix and we decomposed total community
204 variation into pure components and their intersections. Significance was tested by means of a Monte
205 Carlo test with 999 permutations.

206 1.4.3. Taxonomic vs functional composition

207 To test whether anthropogenic pressure causes biotic homogenization in the taxonomic and/or the
208 functional structure of diatom communities (Hypothesis 2), we analysed the taxonomic and
209 functional response of diatom communities. First, we evaluated whether reference and impacted sites
210 differed in their composition of diatom communities. Changes in taxonomic and functional
211 composition (homogenization or differentiation) among the reference and impacted sites were
212 analysed using the test of homogeneity for multivariate dispersion (Anderson et al., 2006) following
213 the procedure proposed by Brice et al. (2017). This test represents a method to evaluate the
214 homogenization within communities belonging to the same category and to compare these values
215 among categories, e.g. among reference and impacted sites or among the calcareous and siliceous
216 HERs. The test of homogeneity for multivariate dispersion was performed with the function
217 “betadisper” in the package *vegan* (Oksanen et al., 2018). The taxonomic matrix, with the relative
218 abundance of each recorded taxon in each sample, was converted into a site-by-site distance matrix
219 using the Bray-Curtis distance, to which the test was applied. The distance of each site to its associated
220 group multidimensional median was calculated and differences among such site distances were tested

221 by means of multivariate analogue of the Levene's test for homogeneity of variance with 9,999
222 permutations to determine whether the dispersions between the two groups were different. We then
223 repeated the test of homogeneity for multivariate dispersion on a functional matrix, containing trait
224 abundances for each sampled site. To generate the functional matrix, we first created a species-by-
225 trait matrix that was multiplied by the species-by-site matrix to obtain the site-by-trait matrix with
226 the function "functcomp" in the package *FD* (Laliberté et al., 2014), in which each entry corresponds
227 to the sum of the relative abundances of all the species present in a site that have a particular trait
228 state. Functional traits considered for generating the functional matrix were life-forms, ecological
229 guilds, size classes and biovolume (Rimet and Bouchez, 2012). We also tested shifts in taxonomic
230 and functional composition between reference and impacted sites with a PERMANOVA (Anderson,
231 2001) applied on distance matrices, using the function "adonis" in the package *vegan* (Oksanen et al.,
232 2017). PERMANOVA is a non parametric multivariate analysis of variance that measures location
233 differences in centroids of the different categories. Thus, we applied this test for investigating possible
234 taxonomic and/or functional turnover among categories. Statistical significance was tested via 9999
235 random permutations.

236 The same procedure was finally adopted to detect differences between the two HERs, which are
237 proxies of lithological substrates, to test whether geology causes differentiation in diatom
238 composition in pristine but not in impacted sites (Hypothesis 3).

239 *1.4.4. Analysis of functional traits*

240 The set of functional metrics extrapolated from the functional matrix were subjected to a non-
241 parametric Mann-Withtney U-test to test for differences between reference and impacted sites and
242 between the calcareous and siliceous HERs within both reference and impacted sites.

243

244 **2. RESULTS**

245 **2.1. Physical and chemical analyses**

246 Observed values of physical and chemical parameters of reference sites showed low nutrient contents
247 (Tab. 2) thus classifying them as oligotrophic in accordance with the Italian Water Legislation (D.
248 Leg. 152/2006 and successive ones). BOD₅ concentrations never exceeded 2.5mg/L, being included
249 in the range of the first water quality class of the national classification, like COD that on average
250 never exceeded 3mg/L. DO was generally high, and pH ranged from 6.70 to 8.50, according to the
251 riverbed lithology. Impacted sites generally showed lower quality, since, on average, N-NO₃ values
252 were included in the range of the third water quality class (D. Leg. 152/2006 and successive ones),
253 with mean values of 1.90 to 2.02 mg/L on calcareous and siliceous substrates respectively. Despite
254 slightly higher than in reference sites, BOD₅ and COD levels corresponded to a moderate organic
255 level (BOD₅ highest value = 5.1 mg/L; COD highest value = 13.8 mg/L) so as P_{tot} whose maximum
256 value reached 0.17 mg/L.

257 Reference and impacted sites showed significant differences in terms of all chemical parameters,
258 except for temperature and TSS and all variables were higher in impacted than reference sites (Tab.
259 2; Fig. B1). Among reference sites, results of the Mann-Whitney U-test showed that N-NO₃, N_{tot}, P-
260 PO₄, conductivity, hardness and pH were significantly higher in the calcareous than siliceous
261 hydroecoregion, while opposite results were observed for BOD₅ and turbidity (Tab. 2; Fig. B2).
262 Among impacted sites, we observed no significant differences between the two geological substrates
263 (Tab. 2; Fig. B3).

264 **2.2. Diatom community composition**

265 In total, we analysed 64 diatom samples from reference sites and identified 120 taxa. In these samples,
266 the most abundant and frequent species was *Achnantheidium minutissimum*, which was detected in all
267 samples and represented the most abundant and frequent species, with a relative abundance on
268 average of 35% per sample. *Achnantheidium pyrenaicum* (about 16% mean relative abundance),
269 *Achnantheidium lineare* (9%). *Gomphonema pumilum* (8%), *Fragilaria arcus* (6%), *Encyonema*
270 *minutum* (2%), *Fragilaria vaucheriae* (<2%), *Cocconeis lineata* (<2%), *Diatoma mesodon* (<2%)

271 were the most abundant taxa detected in at least 50% of the reference sites. In impacted sites, we
272 analysed 46 diatom samples and identified 128 taxa. Again, *A. minutissimum* was the most abundant
273 (mean relative abundance 12%) and frequent (detected in 98% of the samples) species. Beside *A.*
274 *minutissimum*, 16 species were observed in at least 50% of the samples; among them, *Fistulifera*
275 *saprophila* (about 11% of mean relative abundance), *Cocconeis euglypta* (6%), *Amphora pediculus*
276 (6%), *Mayamaea permitis* (5%), *Nitzschia fonticola* (5%), *A. pyrenaicum* (3%), *Nitzschia*
277 *inconspicua* (3%), *E. minutum* (3%), *Navicula tripunctata* (3%) and *Reimeria sinuata* (2%) were
278 those exceeding 2% of relative abundance. According to the Indicator Species Analysis, several
279 species are exclusive of the two HERs in pristine sites, with 10 species representative of the
280 calcareous HER and 8 species representative of the siliceous HER (Tab. 3). Conversely, only few
281 species are exclusive of the two HERs in impacted sites, with 2 species representative of the
282 calcareous substrates and 4 species representative of the siliceous substrates (Tab. 3). *Fragilaria*
283 *vaucheriae* is shared between reference and impacted sites as an indicator species for the siliceous
284 HER, whereas *Gomponema olivaceum* is representative of both siliceous reference sites and
285 calcareous impacted sites.

286 **2.3. Environmental vs spatial components**

287 We first analysed whether diatom communities in pristine sites are more shaped by spatial factors than
288 in disturbed sites (Hypothesis 1). The partial RDA performed on samples collected in reference sites
289 (Fig. 2a) pointed out the minor role of chemical parameters, which together just explained 4% of the
290 total explained variation. Only four chemical parameters (SO₄, pH, N-NO₃ and DO) were included in
291 the final environmental matrix after forward selection. On the other hand, the spatial matrix, which
292 included seven PCNM vectors referring to both coarse and fine scale spatial autocorrelation after
293 forward selection, and the spatially structured environmental parameters represented the key
294 components in explaining diatom variability between the two HERs (8% and 12% respectively).

295 The partial-RDA performed on samples collected in impacted sites (Fig. 2b), highlighted again the
296 dominant role of the spatial component, which alone explains 15% of the total variance. After forward
297 selection, BOD, COD, Cl, HARD, N-NO₃ and SO₄ were included in the environmental matrix,
298 whereas the spatial matrix included six PCNM vectors at large scale. Chemical parameters resulted
299 important in shaping the communities of the impacted sites, explaining 10% of the total variance. The
300 spatially structured environmental parameters explained 6% of the total variance.

301 **2.4. Taxonomic vs functional composition**

302 Second, we analysed whether anthropogenic pressure causes taxonomic and/or functional
303 homogenization of diatom communities (Hypothesis 2). Visual inspection of the PCoA ordination
304 depicts a clear difference in both taxonomic and functional composition between references and
305 impacted sites (Fig. 3). The results of the test of homogeneity for multivariate dispersion and
306 PERMANOVA (Tab. 4) highlighted how reference and impacted sites show significant different
307 taxonomic composition, with reference sites more homogeneous than impacted sites. However, even
308 if the functional composition was significantly different between reference and impacted sites, we
309 could not detect any homogenization effect. The analysis of the community functional profile (Fig.
310 4) revealed significant higher abundances of *low* and *high profile* species in reference sites, whereas
311 *motile* species were more abundant in impacted sites. Regarding life-forms, adnate species dominated
312 in impacted sites, while pad-attached and stalked species showed significant higher abundances in
313 reference sites.

314 Finally, we analysed whether lithological substrate causes biotic differentiation of diatom
315 communities in pristine but not in impacted sites (Hypothesis 3). When considering reference sites,
316 visual inspection of the PCoA performed on the taxonomic matrix clearly highlighted different
317 species composition in siliceous and calcareous hydroecoregions (Fig. 5). This pattern was further
318 confirmed by the results of the PERMANOVA (Table 4), which revealed significant differences in
319 species composition between the two groups. Results of the test of homogeneity for multivariate

320 dispersion (Fig. 5; Tab. 4) highlighted that taxonomic and functional composition of diatom
321 communities were homogeneous within the two groups, even if a nearly significant difference in
322 terms of heterogeneity between diatom communities collected on siliceous (more heterogeneous) and
323 calcareous (more homogeneous) hydroecoregions were observed in terms of ecological guilds. In
324 particular, with the analysis of functional groups, we could detect how the *high profile* guild was
325 significantly more abundant in the calcareous than siliceous area, while the *low profile* guild showed
326 the opposite trend (Fig. 6). In terms of growth forms, the adnate, pad-attached and mucous-colonial
327 taxa resulted significantly more abundant in the siliceous than calcareous hydroecoregion, whereas
328 the opposite trend was observed for stalked-attached taxa (Fig. 6).

329 Concerning impacted sites, PCoA ordinations performed on the basis of both taxonomical and
330 functional composition displayed an overlap between the two groups (Fig. 5). The test of
331 homogeneity for multivariate dispersion underlined no significant differences between the two HERs,
332 even if results of the PERMANOVA highlighted a slightly significant difference between the two
333 groups in terms of taxonomic composition (Tab. 4). These results were furtherly corroborated by the
334 Mann-Whitney U-test performed on total biovolume and relative abundance of ecological guilds and
335 growth forms, which did not highlight differences between the two HERs (Fig. 6).

336

337 **DISCUSSION**

338 Traditionally, diatoms have been described as cosmopolitan organisms, whose communities are
339 shaped by local environmental features (“everything is everywhere but environment selects”; Baas-
340 Becking, 1934). For several years, this theory has been strengthened by the use of the *wide species*
341 *concept* adopted in the European floras (Krammer and Large-Bertalot, 1986-1991), which led to the
342 “force-fitting” of diatom taxa to “European” names and, as a consequence, to confusion concerning
343 species distribution and diversity, which resulted strongly underestimated (Vanormelingen et al.,
344 2008). However, in recent years, the role of spatial control, strictly associated to the dispersal

345 capacity, has been recognized as an important key factor for the determination of diatom community
346 structure (Soininen, 2007), especially in Alpine streams (Bottin et al., 2014). We here investigated
347 the differential role of environmental variables and spatial factors in driving the community
348 composition in pristine and impacted sites within Alpine streams in NE-Italy. Our results confirmed
349 that, in Alpine streams, differences in the composition of the communities are in part due to dispersal
350 limitation. Previous studies in literature highlighted the importance of spatial variables, even at
351 regional scale. For instance, in 2002, Potapova et Charles, observed that at national-scale (USA
352 rivers), almost one-third of the variation in diatom species composition was explained by spatial
353 factors, about 14% by spatially structured environmental parameters and more than 50% by local
354 environmental features. Soininen (2007) highlighted that spatial component accounted 20-31% of the
355 total variance explaining diatom community variations. However, the same author confirmed that at
356 intermediate scale (i.e. 10-3000 km, corresponding to the scale of the present study), there is a joint
357 control of both historical effects and contemporary ecological features. Dong et al. (2016) found that
358 the spatial component played a significant role in shaping diatom communities (about 12%) even at
359 small spatial extent (maximum distance between sites less than 30 km). In 2017, Marquardt and
360 colleagues highlighted that the variation in compositional dissimilarity of some planktonic diatom
361 communities collected in tropical reservoirs was better explained by geographic distance than local
362 environmental features.

363 In accordance with Bottin et al. (2014), we found a stronger effect of the spatial component in
364 impacted (15%) than in reference (8%) sites. This is in contrast with our initial hypothesis
365 (Hypothesis 1) for which the importance of spatial component should be less evident in those sites
366 affected by anthropogenic disturbance. In particular, we highlighted how environmental conditions
367 in impacted sites likely cause biotic homogenization of diatom communities (Hypothesis 2), causing
368 taxonomic but not functional homogenization. Therefore, the main functions in the community are
369 maintained, while spatial processes likely eliminate some functional redundant species (Leibold and
370 Chase, 2017). Spatial processes determining diatom community composition are controlled by

371 several factors, such as geographical barriers (i.e. spatial distance between sites), topographical and
372 geomorphological features (i.e. high mountains), ecological traits of the species (i.e. their motility)
373 but also by hydrological constraints, like artificial impoundments, which interrupt the longitudinal
374 river connection (Dong et al., 2016). Even if the pressure of chemical parameters is evident in these
375 streams, artificial alterations of hydrological connectivity likely play a major role in determining the
376 structure of diatom community. Although the community spatial structure may be determined by
377 multiple underlying mechanisms, like dispersal limitation, colonization stochasticity (i.e. priority
378 effects) or individual spillover from upstream populations (i.e. mass effect), the analysis of the
379 functional profile of diatom communities supports the role of dispersal limitation because the motile
380 guild is dominant in impacted sites, which has been observed to be associated with both hydrological
381 (Elias et al. 2015; Falasco et al. 2016) and morphological (Smucker and Vis, 2010; Bona et al. 2016)
382 alterations. Our results therefore suggest that considering diatom response not only to trophic
383 conditions but also to physical alterations is crucial in biomonitoring programs.

384 In reference sites, spatially structured environmental variables explain a great part of the total
385 variance. This result suggests how chemical parameters strictly linked to peculiar areas (i.e. to HERs)
386 are the main drivers of diatom community composition, further strengthening the role of geology. In
387 fact, the different lithology characterizing the two hydroecoregions led to significant differences in
388 some important geochemical variables, such as conductivity and hardness, which were higher on
389 calcareous than on siliceous substrates (Rimet et al., 2004), with repercussions on diatom species
390 composition. As already observed in previous studies, hydroecoregion environmental characteristics,
391 like geology, resulted among the most important factors in shaping diatom reference communities of
392 high altitude streams (Tison et al., 2005; Rimet et al., 2004; 2007). This is confirmed by our results,
393 since in reference sites taxonomic composition of diatom communities significantly differed between
394 the two HERs but this is not evident in impacted sites. This result confirms our third hypothesis,
395 underlying that the influence of geology is much more important in reference than impacted sites,
396 where the effect of geology is overridden by chemical parameters. The Indicator Species Analysis

397 confirmed such differences in terms of diatom communities in according with previous findings,
398 highlighting some species as significantly representative of reference conditions on calcareous
399 substrates, i.e. *Gomphonema pumilum* (Cantonati, 1998; Cantonati et al., 2012; Tison et al., 2005;
400 Rimet et al., 2004; 2007; Beltrami et al., 2012), *Gomphonema tergestinum* (Rimet et al., 2005; 2007;
401 Tison et al., 2005) and *Cymbella affinis* (Tison et al., 2003; 2005), and on siliceous substrates, i.e.
402 *Encyonema minutum* (Tison et al., 2005; Cantonati et al., 2012; Beltrami et al., 2012), *Encyonema*
403 *silesiacum* (Rimet et al., 2004; Bona et al., 2007; Beltrami et al., 2012), *Fragilaria vaucheriae* (Rimet
404 et al., 2004; Tison et al., 2005; Beltrami et al., 2012) and *Reimeria sinuata* (Rimet et al., 2004; Tison
405 et al., 2005; Beltrami et al., 2012).

406 We found contrasting results concerning *Gomphonema olivaceum*, which resulted indicator species
407 of siliceous substrates in our reference sites, while typical of the calcareous typologies in other studies
408 (see Rimet et al., 2004; Tison et al. 2005; Beltrami et al., 2012). However, in the present study *G.*
409 *olivaceum* also resulted as indicator species of calcareous substrates in the impacted typologies,
410 suggesting that probably geology is not the main parameter controlling the distribution and abundance
411 of this taxon. Even though *Achnantheidium lineare* did not result among the statistically significant
412 indicator species, we noticed it was mainly abundant on the calcareous hydroecoregion, confirming
413 previous findings in the study area (Beltrami et al., 2012).

414 Diatom communities in the two hydroecoregions within reference sites also differed in terms of
415 functional composition, confirming the significant functional shift obtained with the PERMANOVA.
416 In the siliceous sites, the *low profile* guild dominates the community, suggesting that the hydrological
417 regime differs between the two hydroecoregions. We can hypothesize that rivers flowing on the
418 siliceous substrates are possibly characterized by turbulent flows and unstable substrates, which did
419 not allow the development of a mature three-dimensional periphyton. Conversely, the calcareous
420 hydroecoregion presented more mature and stable communities, dominated by the *high profile* guild,
421 i.e. taxa which tolerate higher nutrient load, but sensitive to physical disturbance, suggesting more
422 stable flow conditions compared to siliceous streams (Rimet and Bouchez, 2012). Our hypothesis is

423 supported by Soininen (2007), who pointed out the role of flow velocity among the key environmental
424 factors shaping diatom composition at local scale. In light of these results, the recent hydrological
425 alteration that is affecting Alpine streams (Falasco et al. 2018; Piano et al. 2019) might represent a
426 serious threat to diatom communities.

427 Conversely, differences in functional composition between HERs were less evident in impacted sites,
428 confirming the absence of both functional homogenization and functional shift detected with the test
429 of homogeneity for multivariate dispersion and PERMANOVA respectively.

430 Overall, our results are in accordance with the observations of Heino (2013) and highlight the
431 possibility that water quality bioassessment based on diatoms should be considered more reliable at
432 small scale. In fact, at drainage basin scale, the species sorting should be more effective than at larger
433 scale, where the importance of the spatial component and dispersal limitation is typically high. As
434 highlighted by Bottin et al. (2014), the effect of the spatial component on the structure of diatom
435 assemblages can represent a background noise in the framework of the river quality assessment, and
436 this should be taken into account especially in those countries, like Italy, covering a broad range of
437 mountain areas. Given that physical barriers limiting dispersal in Alpine streams are mainly
438 represented by orographic borders, the identification of reference sites within each drainage network
439 could represent a solution to this constraint.

440 In addition, although we observed taxonomic homogenization in impacted sites, the turnover of
441 species resulted to be more important than biotic homogenization in shaping diatom communities
442 within Alpine streams. These results suggest that the variance between reference and impacted sites
443 is comparable and that they are characterized by different species, thus strengthening the role of
444 diatoms as bioindicators. In light of these patterns, the implementation of metrics that measure this
445 component (e.g. Hillebrand et al., 2017) should be encouraged in biomonitoring programs.

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625

626 **Tables**

627 Table 1. Characterization of sampling sites (CAL = calcareous HER; SIL = siliceous HER).

SITES	HER	origin	distance from the source/morphology	influence of the upstream basin	n samples	n total
REFERENCE SITES	CAL	intermittent	meandering	null	2	64
		spring	< 10 km		2	
		pluvial/nival	< 5 km		12	
			5-25 km	4		
	SIL	glacial	25-75 km	slight	4	
			< 10 km	not detectable	6	
		pluvial/nival	< 5 km		6	
			5-25 km		28	
IMPACTED SITES	CAL	pluvial/nival	< 5 km	null	4	46
			5-25 km		16	
			25-75 km	strong	8	
		subterranean	slight	2		
	SIL	pluvial/nival	< 10 km	null	2	
			1.24	not detectable	6	
		0.9	8			

628

629 Table 2. average (mean), standard deviation (sd), minimum (min) and maximum (max) values of chemical parameters observed in the calcareous
630 HER (CAL) and in the siliceous HER (SIL) in both reference and impacted sites (N-NO₃ = nitrates; N_TOT = total nitrogen; P-PO₄ =
631 orthophosphates; P_TOT = total phosphorous; SO₄ = sulphates; Cl⁻ = chlorides; BOD₅ = biochemical oxygen demand; COD = chemical oxygen
632 demand; HARD = hardness; COND = conductivity; DO = dissolved oxygen; TEMP = temperature; TSS = total suspended solids; TURB =
633 turbidity).

Sites	HER	value	N-NO ₃ (mg/l)	N_TOT (mg/l)	P-PO ₄ (mg/l)	P_TOT (mg/l)	SO ₄ (mg/l)	Cl ⁻ (mg/l)	BOD ₅ (mg/l)	COD (mg/l)	HARD (mg/l)	COND (μS/cm)	DO (mg/l)	pH	TEMP (°C)	TSS (mg/l)	TURB (NTU)
REFERENCE SITES	CAL	mean	0.700	0.680	0.008	0.010	5.60	0.670	0.521	2.09	132	220	10.9	8.24	8.00	5.00	1.12
		sd	0.200	0.260	0.008	0.012	4.30	0.470	0.102	1.10	36.7	47	0.720	0.190	2.80	0.00	0.954
		min	0.400	0.250	0.005	0.005	1.40	0.200	0.500	2.50	17.0	128	9.40	7.70	4.30	5.00	0.300
		max	1.12	1.28	0.040	0.040	16.4	2.00	1.00	6.20	168	277	12.7	8.40	15.0	5.00	4.20
	SIL	mean	0.330	0.390	0.005	0.012	17.8	0.940	0.80	2.70	51.0	100	10.7	7.60	7.50	12.0	7.12
		sd	0.160	0.230	0.001	0.016	17.6	1.12	0.500	0.800	37.7	66	0.940	0.390	2.80	24.0	17.7
		min	0.100	0.250	0.005	0.005	0.800	0.100	0.500	2.50	5.00	14	9.00	6.70	2.80	5.00	0.200
		max	0.900	1.10	0.010	0.060	58.0	6.20	2.30	5.90	139	250	12.6	8.50	14.0	129	98.0
IMPACTED SITES	CAL	mean	2.02	2.29	0.059	0.045	13.4	7.25	1.30	4.30	190	339	11.4	8.39	9.10	6.00	4.24
		sd	1.21	1.38	0.038	0.035	9.90	4.19	1.00	2.80	63.3	99.0	1.25	0.220	4.00	4.00	4.25
		min	0.500	0.600	0.010	0.005	2.60	0.900	0.500	2.50	42.0	92.0	9.40	7.80	1.00	5.00	0.600
		max	7.50	8.40	0.070	0.160	43.0	19.4	5.10	13.8	291	531	15.2	8.80	17.3	25.0	22.3
	SIL	mean	1.90	2.13	0.056	0.070	42.7	10.5	1.10	5.00	133	267	11.4	8.07	7.80	5.00	3.30
		sd	1.26	1.24	0.031	0.037	70.2	3.19	0.700	2.40	97.3	150	0.960	0.160	3.40	0.00	2.88
		min	0.80	0.900	0.020	0.020	5.30	6.80	0.500	2.50	74.0	157	10.1	7.90	3.00	5.00	1.00
		max	4.00	4.20	0.110	0.130	238	16.5	2.90	9.20	398	975	12.9	8.30	13.6	5.00	11.2

634

635 Table 3. Species resulting indicators of calcareous (CAL) and siliceous (SIL) HER in reference and
 636 impacted sites from the Indicator Species Analysis

SITES	CAL			SIL		
	species	IndVal	P	species	IndVal	P
REFERENCE SITES	<i>Gomphonema pumilum</i>	0.817	0.001	<i>Encyonema minutum</i>	0.844	0.001
	<i>Denticula tenuis</i>	0.678	0.001	<i>Fragilaria vaucheriae</i>	0.831	0.001
	<i>Diatoma erhenbergii</i>	0.640	0.006	<i>Encyonema silesiacum</i>	0.716	0.002
	<i>Cymbella excisa</i>	0.589	0.001	<i>Gomphonema olivaceum</i>	0.699	0.002
	<i>Gomphonema tergestinum</i>	0.520	0.020	<i>Reimeria sinuata</i>	0.686	0.038
	<i>Nitzschia fonticola</i>	0.519	0.039	<i>Psammothidium bioretii</i>	0.539	0.020
	<i>Gomphonema elegantissimum</i>	0.497	0.006	<i>Gomphonema pumilum</i> var. <i>rigidum</i>	0.474	0.026
	<i>Cocconeis placentula</i> var. <i>placentula</i>	0.462	0.018	<i>Achananthidium atomoides</i>	0.447	0.034
	<i>Cymbella affinis</i>	0.424	0.040			
	<i>Cymbella excisiformis</i>	0.405	0.023			
IMPACTED SITES	<i>Gomphonema olivaceum</i>	0.712	0.010	<i>Nitzschia inconspicua</i>	0.814	0.002
	<i>Encyonema ventricosum</i>	0.707	0.004	<i>Fragilaria vaucheriae</i>	0.679	0.046
				<i>Rhoicosphenia abbreviata</i>	0.600	0.020
				<i>Diatoma mesodon</i>	0.513	0.029

637

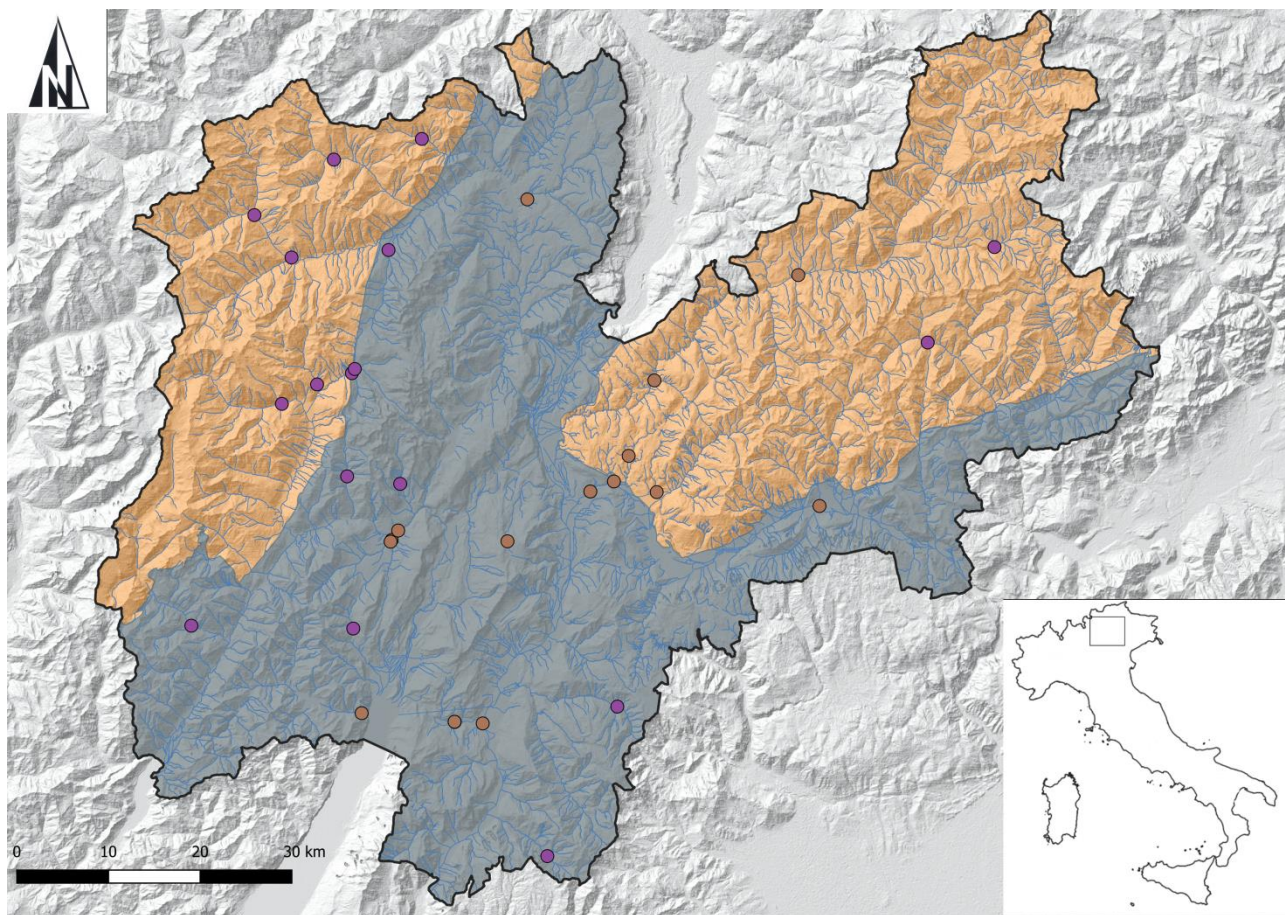
638

639 Table 4. Results of the test for differences in species composition between reference and impacted
 640 sites and between the calcareous (CAL) and the siliceous (SIL) HER within both reference and
 641 impacted sites as inferred from the test of homogeneity for multivariate dispersion and
 642 PERMANOVA analysis. Significant values are highlighted in bold.

	Taxonomic composition	Functional composition
Reference vs impacted sites		
Homogeneity test	$F_{1,108} = 16.2$ $P < \mathbf{0.001}$	$F_{1,108} = 0.140$ $P = 0.709$
PERMANOVA	$F_{1,108} = 24.1$ $P = \mathbf{0.001}$	$F_{1,108} = 49.9$ $P = \mathbf{0.001}$
CAL vs SIL in reference sites		
Homogeneity test	$F_{1,62} = 0.315$ $P = 0.577$	$F_{1,62} = 3.93$ $P = 0.052$
PERMANOVA	$F_{1,62} = 7.32$ $P = \mathbf{0.001}$	$F_{1,62} = 4.81$ $P = \mathbf{0.002}$
CAL vs SIL in impacted sites		
Homogeneity test	$F_{1,44} = 0.194$ $P = 0.662$	$F_{1,44} = 0.598$ $P = 0.444$
PERMANOVA	$F_{1,44} = 1.79$ $P = \mathbf{0.047}$	$F_{1,44} = 1.92$ $P = 0.110$

643

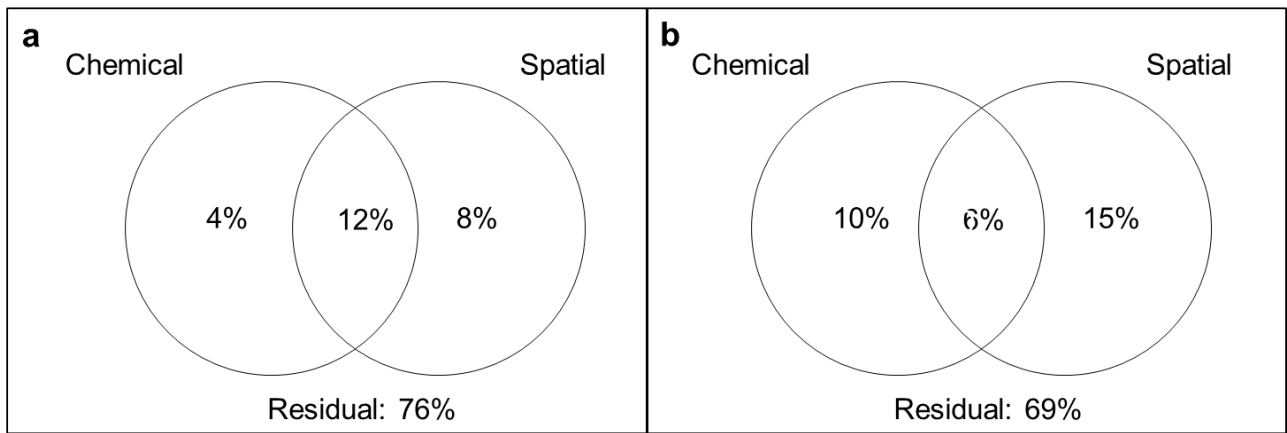
644



646

647 Figure 1. Map of the sampling sites (purple circles = reference sites; brown circles = impacted sites)
648 in the study area (light blue = calcareous HER; orange = siliceous HER).

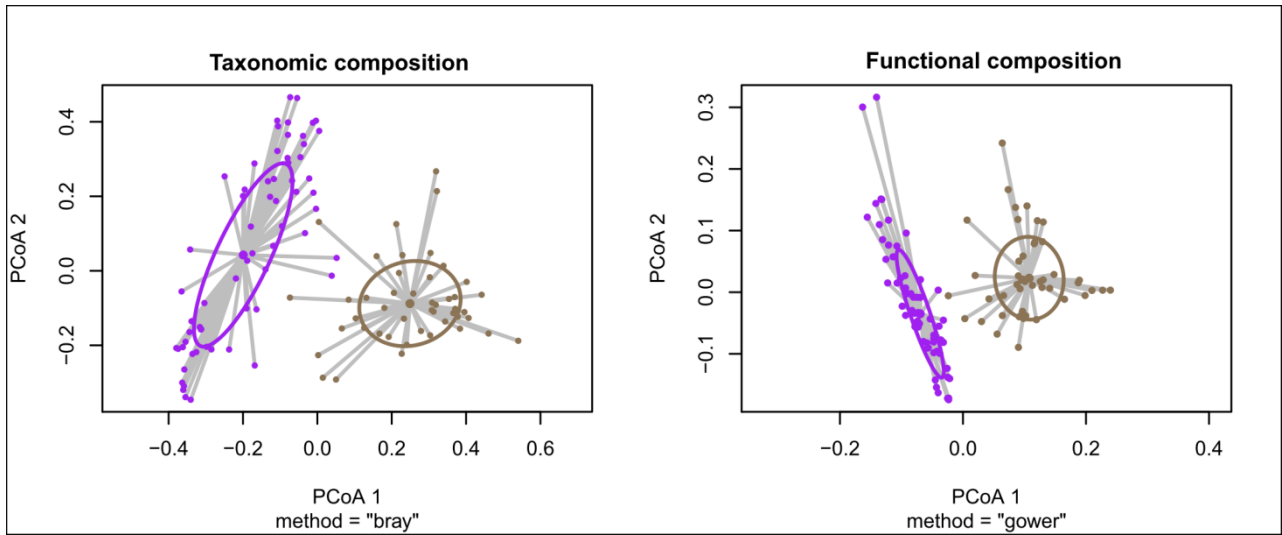
649



650

651 Figure 2. Results from variation partitioning (partial redundancy analysis). The relative contributions
 652 (% of explanation) of chemical and spatial variables, as well as the shared components explaining
 653 variation in diatom communities in reference (a) and impacted (b) sites.

654

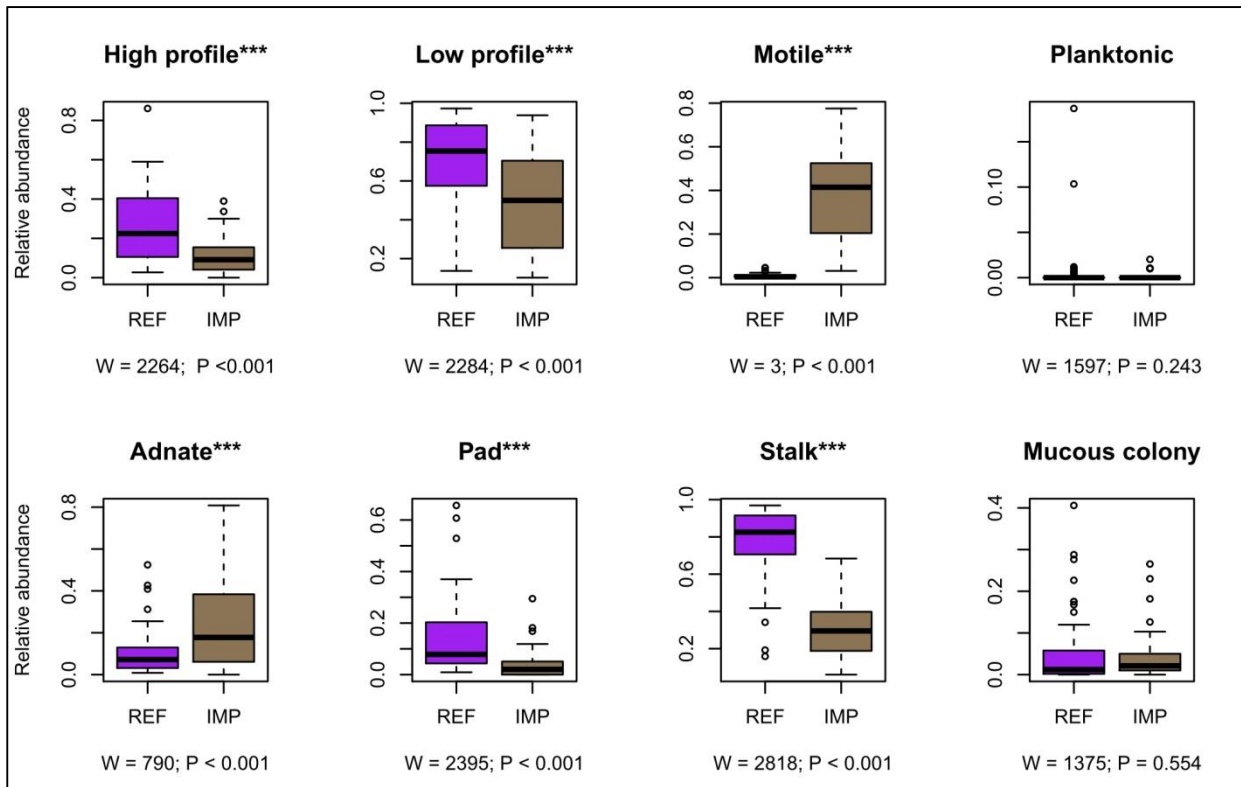


655

656 Figure 3. PCoA ordinations of samples based on taxonomic (left panel) and functional (right panel)

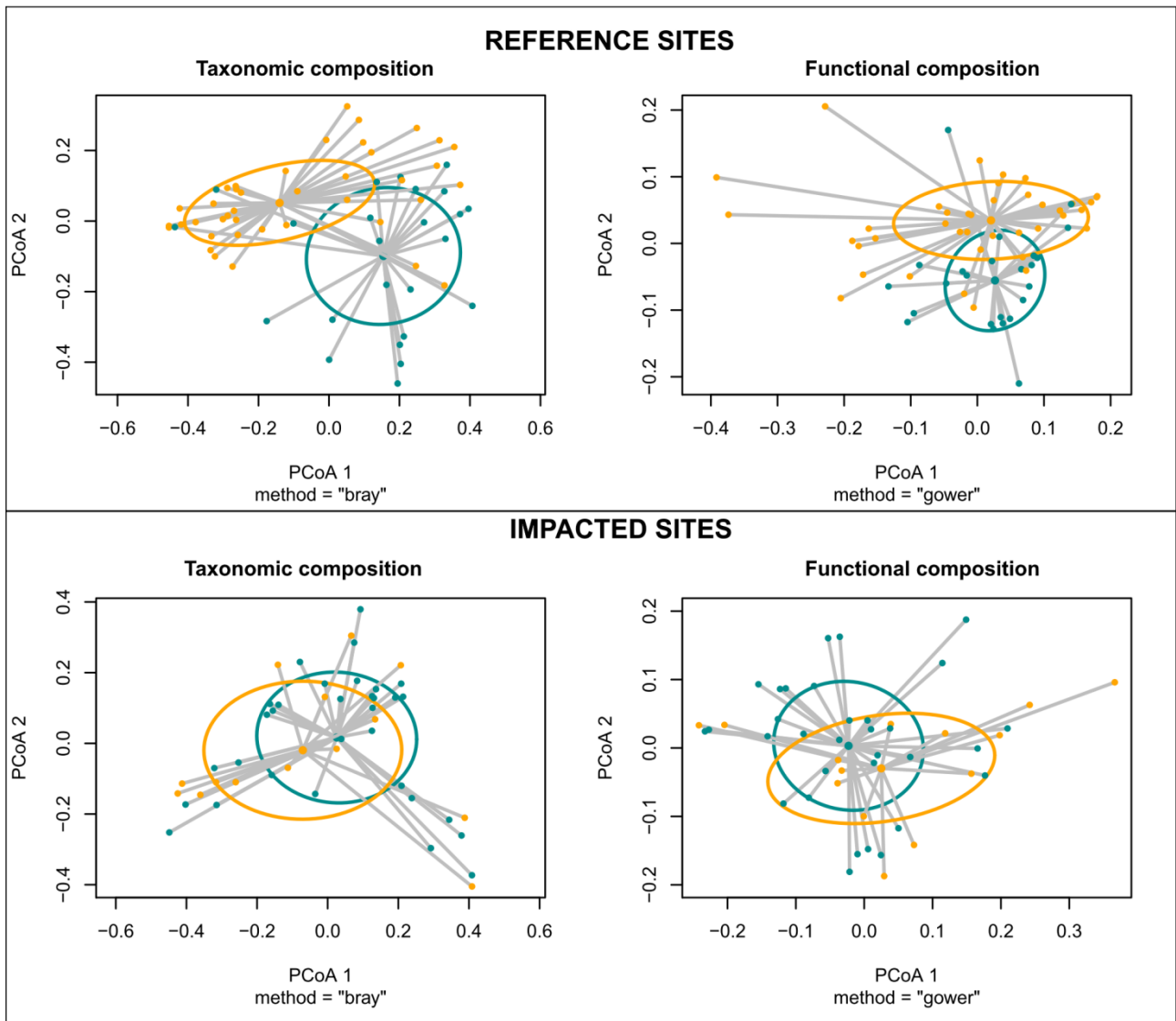
657 composition of diatom communities in reference (purple) and impacted (brown) sites.

658



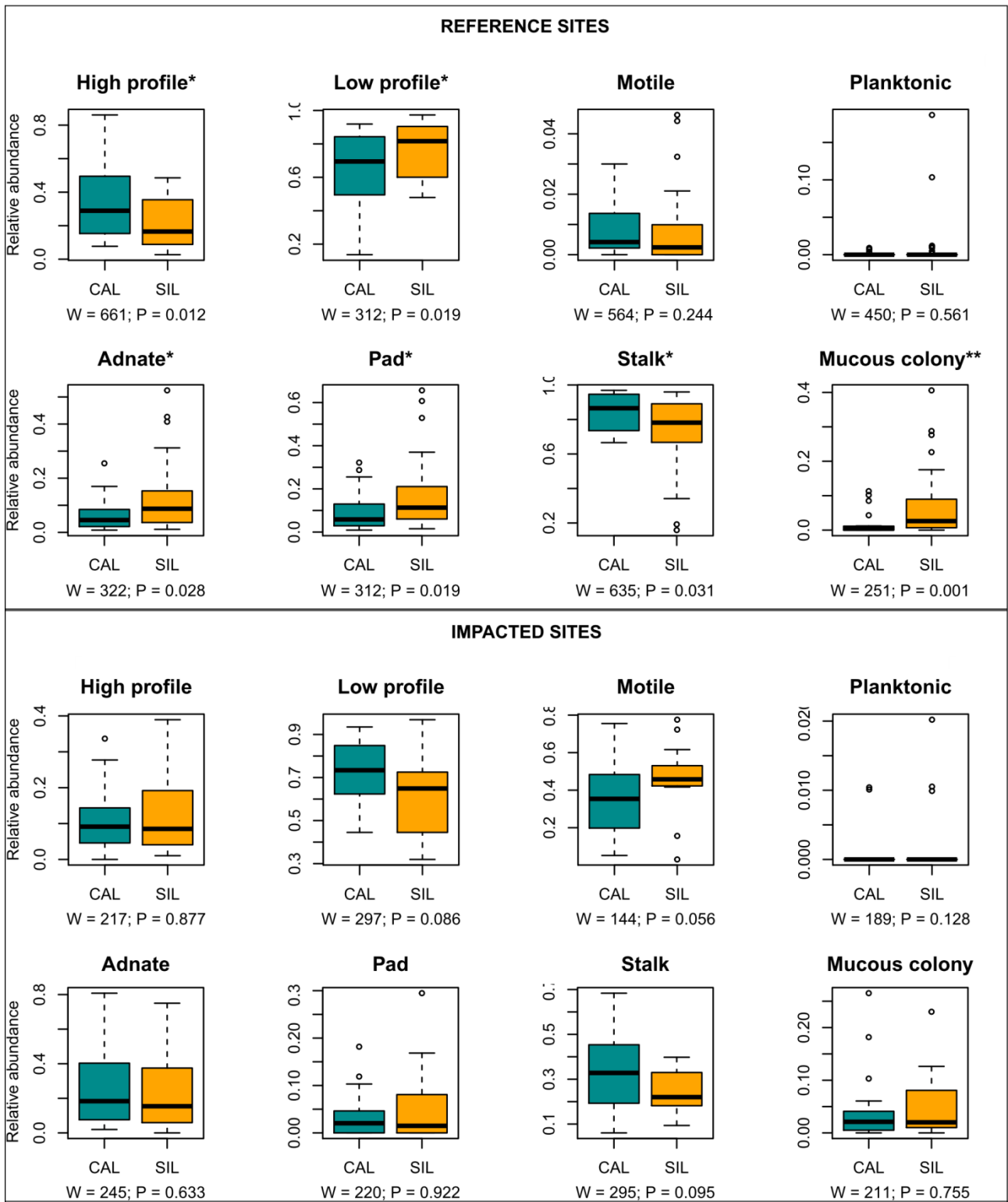
659

660 Figure 4. Boxplots depicting the relative abundances of ecological guilds and life-forms in reference
 661 (purple) and impacted (brown) sites. Results of the Mann-Whitney U-test are reported below each
 662 graph. Asterisks refer to significant differences between the two categories (* < 0.05; ** < 0.01; ***
 663 <0.001).



664

665 Figure 5. PCoA ordinations of samples based on taxonomic (left panel) and functional (right panel)
 666 composition of diatom communities in calcareous (light blue) and siliceous (orange) sites performed
 667 on reference (upper panel) and impacted (lower panel) sites.



668

669 Figure 6. Boxplots depicting the relative abundances of ecological guilds and life-forms in calcareous
 670 (light blue) and siliceous (orange) substrates in reference (upper panel) and impacted (lower panel)
 671 sites. Asterisks refer to significant differences between the two categories (* < 0.05; ** < 0.01; ***
 672 < 0.001).