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1 **The amphipod *Talitrus saltator* as a bioindicator of human**
2 **trampling on sandy beaches**

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19
20 **Abstract**

21 The present paper assesses the use of the supralittoral amphipod *Talitrus saltator*
22 as a bioindicator of the effects of human trampling on the supralittoral sandy band.
23 Samplings in delimited areas were carried out at sites subjected to different human
24 impact. The results showed a strong negative correlation between the number of
25 swimmers and the sandhopper population density, while there was no clear relationship
26 between sandhopper abundance and the other factors considered: granulometry,
27 compactness and organic carbon content of the sand, and trace metal contents in the
28 sand and sandhoppers. A field test of trampling conducted in a confined space showed
29 its direct negative effect on sandhopper survival. However, trace metal analysis
30 confirmed the ability of *T. saltator* to bioaccumulate some elements (Hg, Zn, Cu, Cd).

31 Our study demonstrates that *T. saltator* is a good bioindicator of human impact in the
32 supralittoral zone of sandy shores.

33

34 **Keywords:** Human trampling, Heavy metals, Mediterranean Sandy shores, Beaches,
35 Bioindicator, Amphipod, *Talitrus saltator*.

36

37 **1. Introduction**

38

39 In the coastal zone, the input of materials and substances from terrestrial, fluvial
40 and marine sources is particularly important. In addition to elevated concentrations of
41 nutrients, there can be increased quantities of natural and anthropogenic contaminants.
42 Since the 1960s, European shores (particularly Italian ones) have seen a very strong
43 increase in the number of swimmers at beach resorts. Many studies on the submerged
44 and intertidal littoral environment of rocky and sandy shores have dealt with the use of
45 organisms as biomonitors of trace metal contamination. Similarly, many investigations
46 have attempted to evaluate the effects of human trampling and recreational uses on
47 natural populations and communities of the littoral zone of sandy shores (see Milazzo et
48 al., 2002 for a review). In contrast, the supralittoral band, an ecotonal environment of
49 great ecological importance in the economy of sandy shore ecosystems, has received
50 relatively little attention (see Brown and McLachlan, 1994; Schlacher et al. 2007).

51 Most research on the effects of trampling on natural communities concerns the
52 vegetation or macrofaunal components (especially birds) (Liddle, 1975; Brown and
53 McLachlan, 1994). Several studies have examined the effects of trampling on the
54 invertebrate fauna of rocky shores or of loose substrata of the intertidal zone (for
55 instance see Povey and Keough, 1991; Brosnan and Crumrine, 1994; Chandrasekara
56 and Frid, 1996; Casu et al., 2006; Dye, 2006; Johnson et al., 2007). Instead, there have
57 been very few investigations of the supralittoral fauna of sandy shores and the results of
58 these studies have been contradictory (Jaramillo et al., 1996; Moffet et al., 1998;
59 Weslawski et al., 2000b, c; Veloso et al., 2006). Recent studies have attempted to
60 establish the utility of supralittoral amphipods as indicators of the impact of tourist
61 activities on sandy shores (Fanini et al., 2005). However, because of their methods and
62 sampling sites, the investigations have not provided clear results.

63 In summer, the supralittoral zone is intensely frequented by swimmers but it is
64 also where the major consumers of stranded organic material, i.e. talitrid amphipods and
65 isopod, find shelter during the day, buried in the wet sand. In fact, most of the energy
66 flow deriving from the use of stranded material passes through supralittoral crustaceans
67 (Branch and Branch, 1981; Griffiths et al., 1983; Brown and McLachlan, 1994).
68 Sandhoppers occupy a trophic niche as detritivores and collector-gatherers. Hence they
69 feed on plant and animal material from both marine and terrestrial sources (Palluault,
70 1954; Wildish, 1988; Bergerard, 1989), integrating the two routes of contamination of
71 the supralittoral.

72 The aims of the present study were to examine the possibility of using the
73 amphipod *T. saltator* as a bioindicator of the effects of human trampling on the
74 supralittoral of sandy shores and to provide a simple low-cost monitoring tool. For this
75 reason the relationship between sandhoppers abundance and swimmers has been
76 considered, as well as the possible influence of some other factors such as granulometric
77 composition and sand compactness, organic carbon content in the sand and trace metal
78 contamination.

80 **2. Materials and methods**

82 *2.1 Sandhopper sampling*

84 Samplings to determine the density of sandhoppers were carried out at eight sites on
85 the coast of Tuscany subjected to different tourist impact and either with or without
86 beach cleaning procedures. In the five sites inside the Regional Park of Migliarino, San
87 Rossore, Massaciuccoli (MSRM Park, Pisa), the sampling was performed once a month
88 from June to September 2004, 2005 and 2006:

- 89 O1) Oasi 1 (cleaned beach)
- 90 SM) Serchio Mare (seashore, not cleaned)
- 91 SF) Serchio Fiume (right bank of river mouth, not cleaned)
- 92 BV) Batteria Vecchia (not cleaned)
- 93 FM) Fiume Morto Vecchio (not cleaned)

94 At the three sites along the Feniglia sandbar (southern Tuscany, Grosseto), the
95 sampling was performed in July and September 2005:

96 FA) bathhouse (Ansedonia side, cleaned beach)

97 FB1) beach ca. 1 km from FA (cleaned)

98 FB2) beach ca. 2 km from FA (cleaned)

99 At each sampling, all the sandhoppers were captured (also disturbing the surface
100 layer to sample those in the sediment) and counted inside four areas (75 cm² each)
101 delimited by plastic containers inserted a few cm into the sand. Each container was
102 inserted along the sea-land axis of the beach at a progressively increasing distance
103 starting from the water line until the beginning of dry sand. At each site, the sampling
104 was carried out twice, a few meters apart, since the distribution of sandhoppers in the
105 band of wet sand does not seem to be uniform (Weslawski et al., 2000a).

106 At each sampling site, the people to the right and left of the shoreline, along a
107 150 m transect in the central hours of the day on the days with the highest tourist
108 presence, were also counted (Saturday and Sunday).

109 At some locations, the following factors were also analyzed to exclude
110 differences between the sampling sites: 1) contents of trace metals in the sand and in the
111 sandhoppers (Hg, Cr, Cd, Cu, Zn, Fe, Al, Pb); 2) compactness of the sand; 3)
112 granulometric composition of the sand; 4) organic carbon content of the sand.

113

114 2.2 *Trace metals*

115

116 The trace metal analysis was conducted on sand samples collected from the zone
117 frequented by the sandhoppers during the day and on adult individuals of *T. saltator*
118 collected at all the sites. The animals were transported to the laboratory in plastic
119 containers with sand and detritus from the sampling site and then sacrificed by freezing.
120 At each site, a sample of sand was collected in the zone frequented by the sandhoppers
121 during the day. We dehydrated the samples at 40°C until they reached a constant weight
122 and then were finely ground. Around 150 mg of each sample were mineralized in
123 Teflon vessels containing 3 ml of HNO₃ at 120°C for 8 h. After digestion, the solution
124 was brought to a volume of 10 ml by addition of deionized water. During each

125 mineralization, we performed several “blank trials”, by putting only the reagents in the
126 Teflon containers, to verify the absence of contamination.

127 The analyses were performed by atomic absorption spectrometry. Cd, Cr, Cu
128 and Pb were determined by atomization with a graphite furnace and Zeeman
129 background corrector. The FIMS (Flow Injection Mercury System) was used for Hg,
130 while we determined Al, Fe and Zn by Inductively Coupled Plasma Atomic Emission
131 Spectrometry (ICP/EAS). Each analysis was carried out 3 times and the accuracy of the
132 analytical procedures was assessed by comparing the results of contemporary digestions
133 and analyses of Standard Reference Materials, SRMs): SRM 1566a “oyster tissue” from
134 the National Institute of Standards and Technology (NIST, Gaithersburg, USA). The
135 results of the determination were only accepted if the values measured for the SRMs
136 were within the certified concentration range; if not, we repeated the analyses. The
137 element concentrations (expressed as $\mu\text{g/g}$) were calculated by the method of “internal
138 additions”. The coefficients of variation for the various elements were between 5 and
139 10%.

140

141 2.3. *Granulometric composition and sand compactness*

142

143 For the granulometric analysis, the sand samples were split to obtain samples of
144 approximately 10 grams (the choice of the representative volume was based on the
145 median of the sediment, as estimated by visual examination).

146 A statistically representative portion of the sample was placed in an oven at 80°C to
147 eliminate the humidity, after which we sifted the material through a series of
148 progressively finer sieves ($2500\ \mu\text{m}$, $1600\ \mu\text{m}$, $1000\ \mu\text{m}$, $630\ \mu\text{m}$, $400\ \mu\text{m}$, $250\ \mu\text{m}$, 160
149 μm , $100\ \mu\text{m}$, $63\ \mu\text{m}$) for around 5 minutes with a Ro-Tap shaker. Since the samples
150 were prevalently sandy, it was not necessary to analyze the mud-clay fraction ($< 63\ \mu\text{m}$)
151 of the sediment.

152 To assess the compactness of the sand in the zone frequented by sandhoppers
153 during the day, an aluminum pole was dropped from a height of 1 m and the distance
154 the pole penetrated into the sand was measured. The distance was transformed into
155 arbitrary units by assigning a value of 100% compactness to 0 cm and 50%
156 compactness to 10 cm.

157

158 2.4. *Organic carbon*

159

160 The sand samples were collected at each site in July 2006. The organic carbon in
161 the sand samples was determined as the difference between the total carbon and the
162 inorganic carbon. The sand was crushed to a fine powder so as to homogenize the
163 sample. Total carbon was determined with a CHNS/O ANALYZER (mod. 2400 ser. II,
164 Perkin Elmer), while inorganic carbon was measured with a De Astis calcimeter.

165

166 2.5. *Trampling test*

167

168 The trampling test was carried out at Fiume Morto Vecchio (MSRM Park). Two
169 plastic cylinders (110 cm diameter) were fixed in the sand in the wet band frequented by
170 sandhoppers during the day. All the individuals inside each of the delimited areas were
171 captured, counted and then freed within the same area. After around 15 minutes
172 (sufficient time for the sandhoppers to return to their refuges in the wet sand), two
173 people performed 400 footsteps in 15 minutes inside one of the two cylinders. The
174 number of footsteps was chosen on the basis of the footsteps recorded during a survey
175 carried out from 11:00 to 12:00 on a Saturday in July 2006 on the Marina di Pietrasanta
176 beach (a popular beach on the Tuscan coast). During this survey, a mean transit of 866
177 swimmers per hour at a selected point on the shoreline was recorded. The sandhoppers
178 within the other cylinder were left undisturbed. At the end of the trial, the sandhoppers
179 still alive in both cylinders were captured, counted and transported to the laboratory in
180 basins with wet sand. The numbers of individuals still alive 24 hours after the treatment
181 was also recorded.

182

183 2.6. *Statistical analysis*

184

185 The granulometric data were analyzed with specific software (Dept. of Earth
186 Sciences, Univ. of Florence) that provided parametric statistics indicative of the sorting
187 of the samples, as well as the percentages of the granulometric classes for the purposes
188 of textural classification (Shepard, 1954).

189 The statistical analysis of sandhopper density was performed independently of
190 an analysis of natural population fluctuations (see Anastácio et al., 2003; Marques et al.,
191 2003) and/or a comparison of the population densities at different sites. Such analyses
192 were beyond the scope of our study and would not have provided information useful for
193 our aims. It is possible that sandhopper populations living in the same environment and
194 practically at the same latitude (ca. 200 km apart) present small differences in the
195 natural fluctuation of population density. However, since we performed relative
196 comparisons of the number of captured individuals among several localities of the same
197 zone, any differences in population density between different zones in the same period
198 of the year would not affect the interpretation of the results. The tests used are among
199 the most common ones in non-parametric statistics (Zar, 1984; Siegel and Castellan,
200 1989).

201 The possible influence of trace metal pollution on sandhopper density was
202 assessed with the Spearman rank-order correlation coefficient test (Siegel and Castellan,
203 1989). In the figure illustrating trace metal pollution, we arranged the sampling sites in
204 decreasing order of sandhopper density: the site with the highest sandhopper abundance
205 in July 2006 (FM, captured sandhoppers = 1013) was given the arbitrary value of 100.
206 The values for the other sites were expressed as a percentage of FM.

208 **3. Results**

209 **3.1 Sandhopper density**

210 The frequency of *T. saltator* individuals collected at the MSRM Park sites was
211 negatively correlated with the frequency of swimmers (Fig. 1). Despite the small sample
212 sizes, statistical significance was reached for each of the four months (June-September)
213 (June and July, $r_s = -1$, $p = 0.01$; August and September, $r_s = -0.925$, $n = 5$, $p < 0.05$, $n =$
214 5, Spearman rank-order correlation coefficient test, Fig. 1). This is also confirmed
215 considering the mean number of sandhoppers and swimmers (Table 1). In fact, the
216 Fiume Morto Vecchio site (FM) consistently had the lowest tourist impact and the
217 highest sandhopper abundance (Table 1). In contrast, no sandhoppers were found at the
218 site with the highest tourist impact, Oasi 1 (Table 1).
219
220

221 **FIG. 1**

222

223 **TABLE 1**

224 The July vs. September comparison for the various sampling sites was
225 statistically significant for the localities in the MSRM Park ($G = 114.5$, $df = 4$, $p < 0.001$,
226 fig. 1) but not for the sites on the Feniglia sandbar ($G = 1.9$, $df = 2$, $p > 0.1$, G test, Fig 3).

227 There was a significant monthly difference in sandhopper abundance even at a
228 single locality with very low tourist impact (Fiume Morto Vecchio, Table 1, Fig. 2, $G =$
229 664 , $df = 1$, $p < 0.001$, G test) due to the natural population fluctuation. However, these
230 differences did not affect the swimmers-sandhoppers relationship.

231 **FIG. 2**

232

233 It was not possible to make statistical comparisons for the Feniglia sandbar (Fig.
234 3) because of the small number of sampling sites. Nevertheless, the number of
235 sandhoppers captured at the Feniglia sites clearly followed the same trend in relation to
236 tourist impact as the one recorded at the MSRM Park sites, i.e. localities with higher
237 tourist impact had lower *T. saltator* densities.

238 **FIG. 3**

239

240 Regarding the possible influence of beach cleaning on sandhopper survival,
241 there was a significant difference between the only cleaned site (O1, $n = 0$) and the total
242 of the other MSRM sites (SM + SF + BV + FM, $n = 7\ 551$; $G = 10\ 434$, $df = 1$,
243 $P < 0.0001$, G test). However, there were also significant differences among the not
244 cleaned sites (SM, $n = 28$; SF, $n = 164$; BV, $n = 2160$; FM $n = 5\ 199$; $G = 10\ 077$, $df = 3$,
245 $P < 0.0001$, G test). A similar result was obtained for the cleaned beaches of the Feniglia
246 sandbar (FA, $n = 131$; FB1, $n = 41$; FB2, $n = 3$; $G = 164$, $df = 2$, $P < 0.01$, G test).

247

248 3.2 *Trace metals*

249

250 At the sites with sandhoppers, the Cu, Cd, Hg and Zn concentrations (Fig. 4)
251 were constantly higher in the sandhoppers than in the sand. In contrast, the Fe, Pb and
252 Al contents (Fig. 4) were higher in the sand than in the sandhoppers. For Cr, there was a

253 higher concentration in the sandhoppers at two sites and in the sand at the other two
254 sites.

255 There was no significant correlation between sandhopper abundance (in Fig. 4
256 abscissa, the sites are in decreasing order of abundance) and trace metal contents in the
257 individuals or in the sand ($P = NS$ in each case, $n = 6$, Spearman rank-order correlation
258 test).

259 **FIG. 4**

260

261 3.3. *Granulometric composition and sand compactness*

262

263 The granulometric composition of the sand was fairly uniform among sites: all
264 samples were well classified and in the medium- to coarse-grained range (Table 2).

265 **TABLE 2**

266

267 For the MSRM Park sites, there was no correlation between mean sand grain
268 diameter and sandhopper density (Spearman rank-order correlation coefficient test, $r_s =$
269 -0.1 , $n = 5$, $p = NS$, Fig. 5A). A qualitative evaluation also suggested a lack of
270 correlation between sandhopper abundance and mean sand grain diameter at the
271 Feniglia localities (Fig. 5B).

272 Sand compactness at the MSRM Park sites (Fig. 5C) was not significantly
273 correlated with the number of sandhoppers ($r_s = -0.175$; $n = 5$, $p = NS$, Spearman rank-
274 order correlation coefficient test). Indeed the highest values occurred at site SF where
275 sandhoppers were present (Fig. 5C). For the Feniglia sites, a qualitative evaluation
276 indicated a negative correlation between sand compactness and sandhopper abundance
277 (Fig. 5D).

278

279 3.4. *Organic carbon*

280

281 For the MSRM Park sites, the organic carbon content of the sand was not
282 significantly correlated with sandhopper density ($r_s = 0.7$, $n = 5$, $p = NS$; Spearman
283 rank-order correlation coefficient test, Fig. 5E). However, the localities along the
284 Feniglia sandbar showed a negative correlation between the two parameters (fig. 5F).

285 **FIG. 5**

286

287 3.5. *Trampling test*

288

289 The effect of trampling on *T. saltator* survival (Fig. 6) was evident immediately
290 after the treatment: the difference between the number of live individuals before and
291 after treatment was highly significant ($G = 86$, $df = 1$, $p < 0.001$, G test). After 24 hours,
292 the percentage of surviving sandhoppers dropped almost to zero ($G = 428$, $df = 1$,
293 $p < 0.001$, G test) while the survival of the control sandhoppers remained the same.

294 **FIG. 6**

295

296 **4. Discussion**

297

298 Of all the factors that might have negatively influenced the population density of
299 *T. saltator*, only the number of swimmers showed a significant correlation with the
300 number of captured sandhoppers. Although the effect of trampling in a confined test
301 space is probably not the same as in natural conditions (in which case the animals could
302 escape), our test results are the first direct proof that human trampling affects
303 sandhopper survival. This is likely an important factor at Mediterranean latitudes and
304 for species that burrow only slightly into the sand (ca. 3- 5 cm depth).

305 This does not mean that other factors are never influential, only that they are not
306 particularly important in the conditions encountered in this study. Sand compactness
307 probably has a negative effect on sandhopper abundance beyond a certain threshold: a
308 particularly compact substrate could hinder burrowing, thus reducing the probability of
309 survival. However, sites like BV and SF, where sandhoppers were present, had more
310 compact sand than O1, where sandhoppers were never found. The negative correlation
311 at the Feniglia sites probably depended on the fact that the increasing order of sand
312 compactness at the sites corresponded to an increasing order of tourist impact.
313 Furthermore, the sand compactness at O1, where sandhoppers were absent, was lower
314 than at FB2 and FB1 where sandhoppers were present. Therefore, sand compactness
315 does not seem to be a primary determinant of *T. saltator* population density.

316 There did not appear to be any relationship between sandhopper abundance and
317 sand grain size at the various sites. In fact, *T. saltator* lives on beaches with sand that
318 ranges from medium- to coarse-grained (i.e. from around 0.5 to 2 mm, Ugolini et al.,
319 1995). All the locations considered in this study fell within this range.

320 The results for organic carbon suggested a negative correlation with sandhopper
321 abundance at the Feniglia sandbar sites. However, as for sand compactness, the
322 increasing order of organic carbon content at the sites corresponded to an increasing
323 order of tourist impact. In addition, the FM site (MSRM Park) had a high sandhopper
324 abundance but a higher organic carbon content than at FA where there were very few
325 sandhoppers (but many swimmers).

326 The trace metal analysis confirmed *T. saltator*'s good ability to bioaccumulate
327 Hg, Cu, Cd and Zn (Rainbow and Moore, 1986; Moore and Rainbow, 1987; Rainbow,
328 1998; Rainbow et al., 1998a, b; Marsden and Rainbow, 2004; Ugolini et al., 2004,
329 2005). Although there were some differences in trace metal contamination among sites,
330 there was no clear relationship with the abundance of sandhoppers. Hg accumulation
331 seemed to be negatively correlated with sandhopper abundance at the various sites (Fig.
332 4). Nevertheless, the Hg concentration in the sand was lowest at O1 where there were
333 no sandhoppers. Thus, the absence of sandhoppers at O1 and the low density at FA
334 cannot be attributed to Hg contamination. Furthermore, the trace metal concentrations in
335 both the sandhoppers and sand samples were much lower than those recorded
336 previously at heavily polluted localities where sandhoppers or beachflies were present
337 (Rainbow et al., 1998a, b; Fialkowski et al., 2000; Ugolini et al., 2004).

338 Since we did not evaluate the effects of beach cleaning separately from the
339 effects of trampling, we cannot exclude a possible influence of beach cleaning on
340 sandhopper density. Nevertheless, at the sampling sites not subjected to mechanical
341 beach cleaning, sandhopper abundance still varied in relation to the different tourist
342 impact. In fact, the sandhopper distributions along the Feniglia sandbar (where the
343 beach is regularly cleaned) and at Fiume Morto Vecchio and Batteria Vecchia (where
344 beach cleaning is not carried out) all presented the same pattern in relation to the
345 numbers of swimmers. Therefore, contrary to the hypothesis of Fanini et al. (2005),
346 trampling rather than beach cleaning has a negative effect on the survival of
347 sandhoppers. We can also add a qualitative datum: at site O1, the one with the highest

348 tourist impact in the MSRM Park, we never captured any sandhoppers during the
349 present research, whereas hundreds of sandhoppers were regularly collected around 25
350 years ago when the zone had no beach resorts and swimming was forbidden.

351 We studied populations living within 200 Km of each other and thus subject to
352 very similar general climatic and environmental conditions. Therefore, the natural
353 fluctuations of population density are probably synchronous. In any case, since the
354 proposed method is based on the comparison of densities recorded at the various sites in
355 the same time period, it is independent of natural population fluctuations and does not
356 require biodiversity estimates for the considered environment. Hence, the method is
357 simple and low-cost. Other recently proposed methods using sandhoppers to assess
358 human disturbance are based on quantification of the variability of spatial-temporal
359 habitat use (ElGtari et al., 2002; Nardi et al., 2003; Fanini et al., 2005; Scapini et al.,
360 2005) or on determination of the degree of genetic variability (Ketmaier et al., 2003).
361 However, *T. saltator*'s high behavioral plasticity and remarkable ability to learn new
362 directions of the sea-land axis of the beach (see Ugolini and Macchi, 1988; Ugolini and
363 Scapini, 1988; Ugolini et al., 1988) prevent a reliable and rapid determination of the
364 reasons for variability in orientation behavior. The determination of genetic variability
365 is interesting but not easily performed. Therefore, since these methods require specific
366 expertise in various fields, sophisticated analytical techniques and complex statistical
367 analyses, their practical application appears to be problematic.

368 The effect of human trampling and heavy tourist use of beaches on sandhopper
369 populations raises the question of their conservation. *T. saltator* is a good osmoregulator
370 (Morritt, 1988; Calosi et al., 2007) and metapopulations of this species are also found
371 on the shores of retrodunal pools and on riverbanks near the mouth (Ugolini and
372 Macchi, 1988; Ugolini and Scapini, 1988; Ugolini et al., 1988). These places are usually
373 shunned by swimmers and if protected could be valid reserves for natural (spontaneous
374 migrations) or artificial sandhopper repopulation of the adjacent beaches.

375 In conclusion, 1) our method is reliable and low-cost, 2) *T. saltator* is a good
376 biomonitor of trace metal pollution (Cu, Hg, Zn, Cd), and 3) this species is a valid
377 bioindicator of the effects of human trampling and could be used for ecocompatible
378 management of the tourist impact on the supralittoral zone.

379

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381

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386

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506 **Table captions**

507

508 Table 1. Captured sandhoppers and number of swimmers (mean \pm SD; n = 3) for each
509 month of sampling

510

511 Table 2. Results of the granulometric analysis for each sampling site. For further
512 explanations, see Figs. 1, 3 and text.

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517 **Figure captions**

518

519 Fig. 1. Frequency (% of total numbers) of captured sandhoppers (black bars) and
520 swimmers (white bars) for each month of sampling. The order of the sampling sites is
521 based on the number of swimmers observed at each locality: FM = Fiume Morto; BV =
522 Batteria Vecchia; SF = Serchio Fiume; SM = Serchio Mare; O1 = Oasi 1. The total
523 numbers of sandhoppers and swimmers at all five sites are also given.

524

525 Fig. 2. Monthly variation of sandhopper numbers (% of total sampled) at Fiume Morto
526 (FM). Total number of sandhoppers collected = 5199.

527

528 Fig. 3. Frequency (% of total numbers) of captured sandhoppers (black bars) and
529 swimmers (white bars) along the Feniglia sandbar in July and September. The order of
530 the sampling sites is based on the number of swimmers observed at each locality: FA =
531 Feniglia bathhouse, FB1 = 1 km from bathhouse, FB2 = 2 km from bathhouse. The total
532 numbers of sandhoppers and swimmers at all three sites are also given.

533

534 Fig. 4. Trace metal concentrations ($\mu\text{g g}^{-1}$ dry wt) in the sand (white bars) and in the
535 sandhoppers (black bars). For each element, the sampling sites are ordered according to
536 decreasing frequency of sandhoppers recorded in July 2006. For further explanations,
537 see Figs. 1, 3 and text.

538

539 Fig. 5. A-B: mean sand grain diameter (white bars) and frequency of captured
540 sandhoppers (black bars; % of total numbers). The order of the sampling sites is based
541 on mean diameter. C-D: sand compactness (white bars) expressed in arbitrary units (a.
542 u.) and frequency of captured sandhoppers (black bars). The order of the sampling sites
543 is based on sand compactness. E-F: percentage of organic carbon in the sand (white
544 bars) and frequency of captured sandhoppers (black bars). The order of the sampling
545 sites is based on percentage of organic carbon. For further explanations, see Figs. 1 and
546 3.

547

548 Fig. 6. Frequency of surviving sandhoppers subjected to the trampling test (black bars)
549 and controls (white bars). Before = before the test, After = after the test, 24h = 24 hours
550 after the beginning of the test. See text for further details.

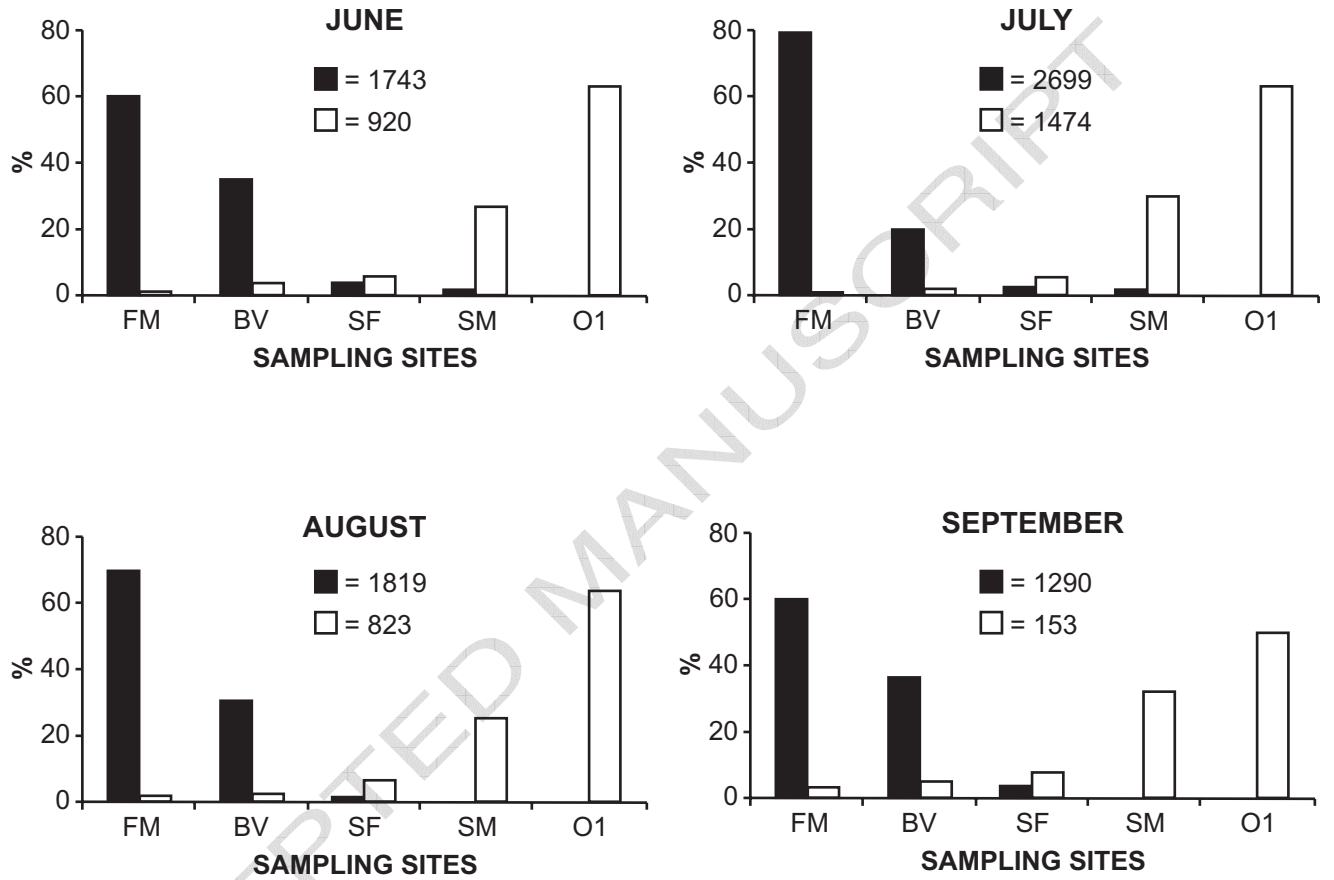
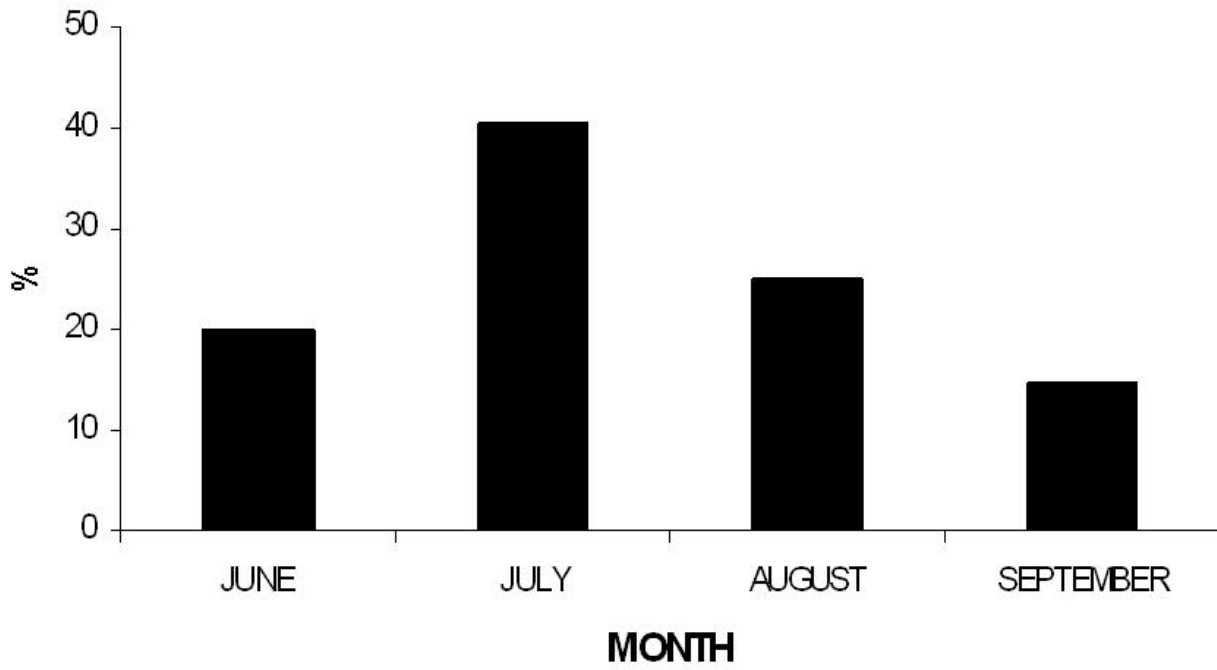


Figure 1



Figure

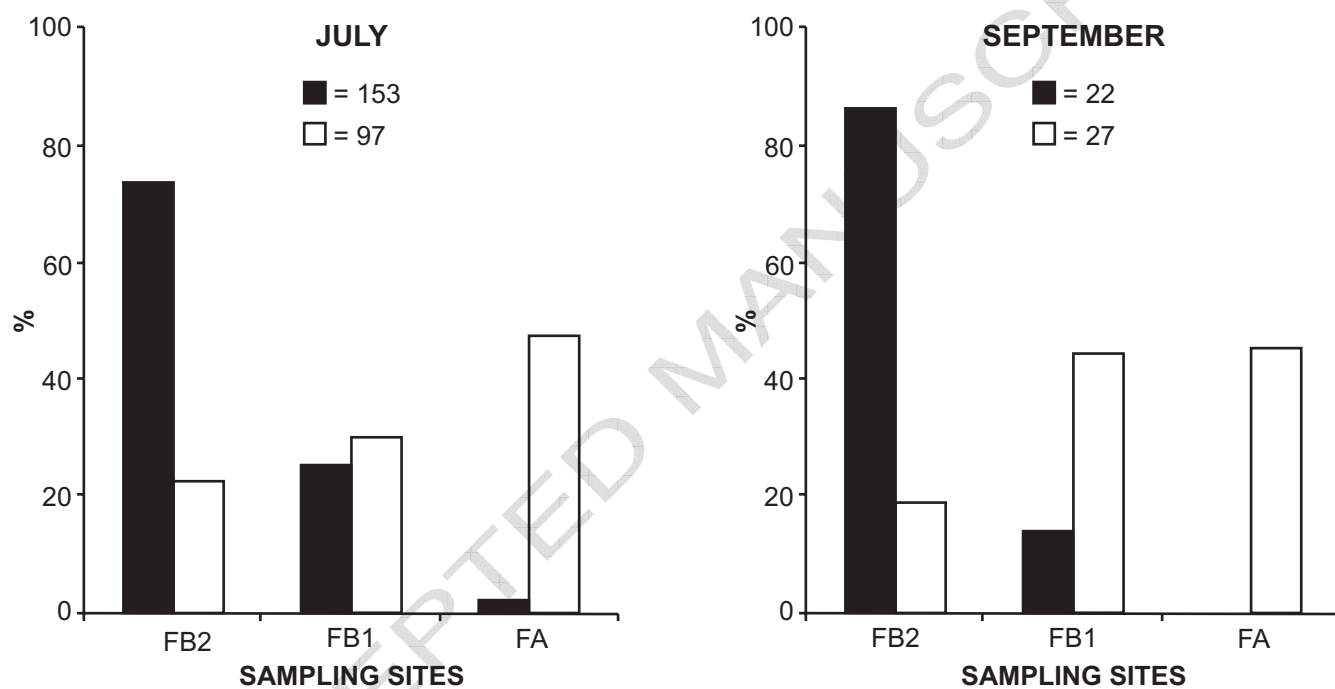


Figure 3

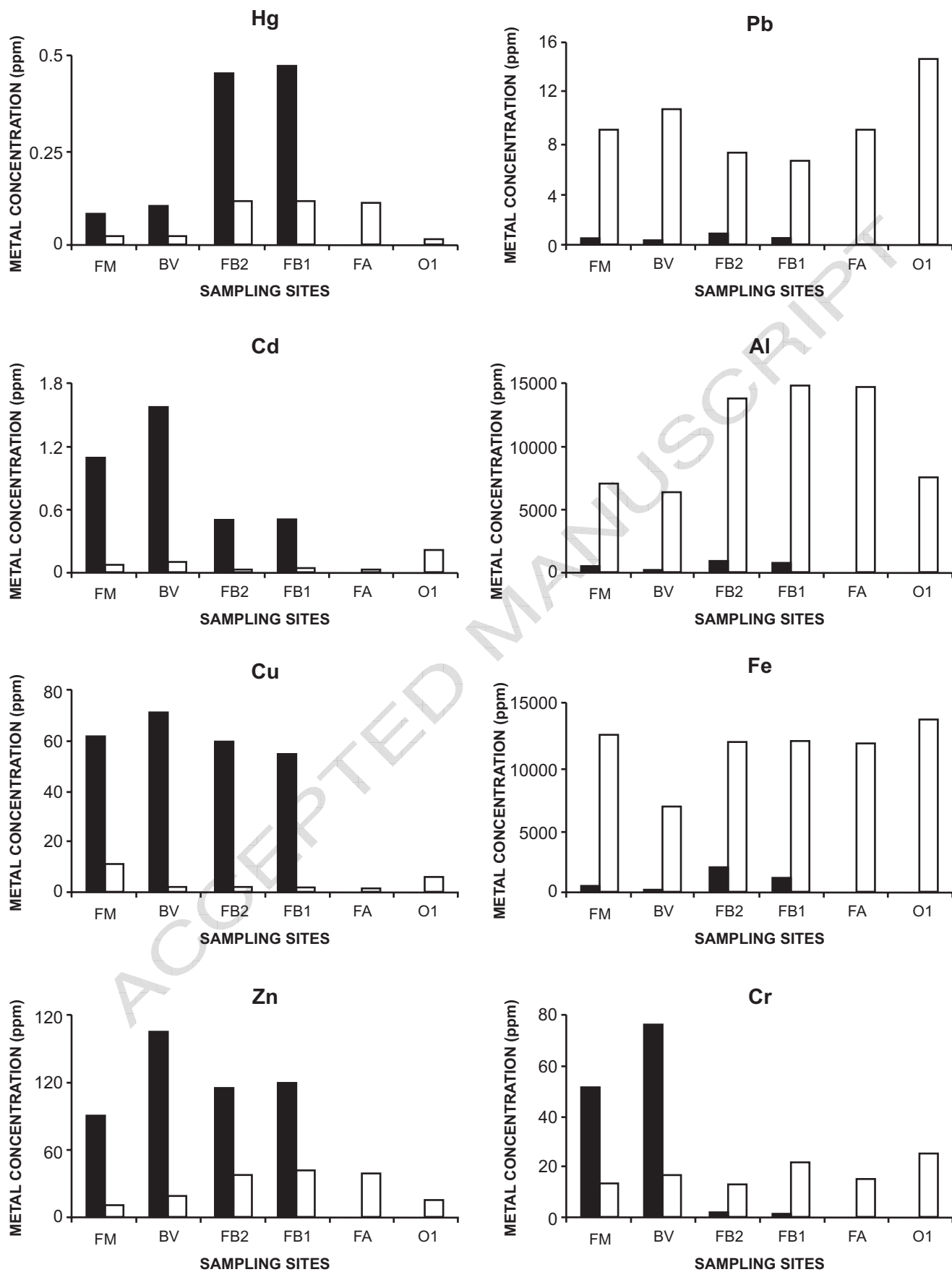
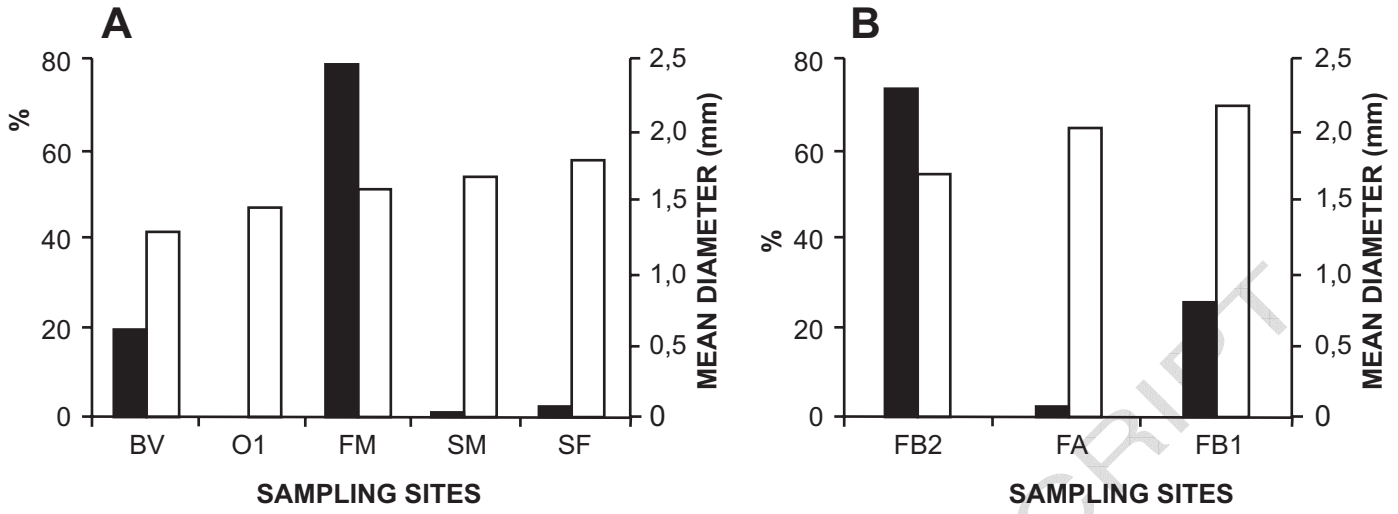
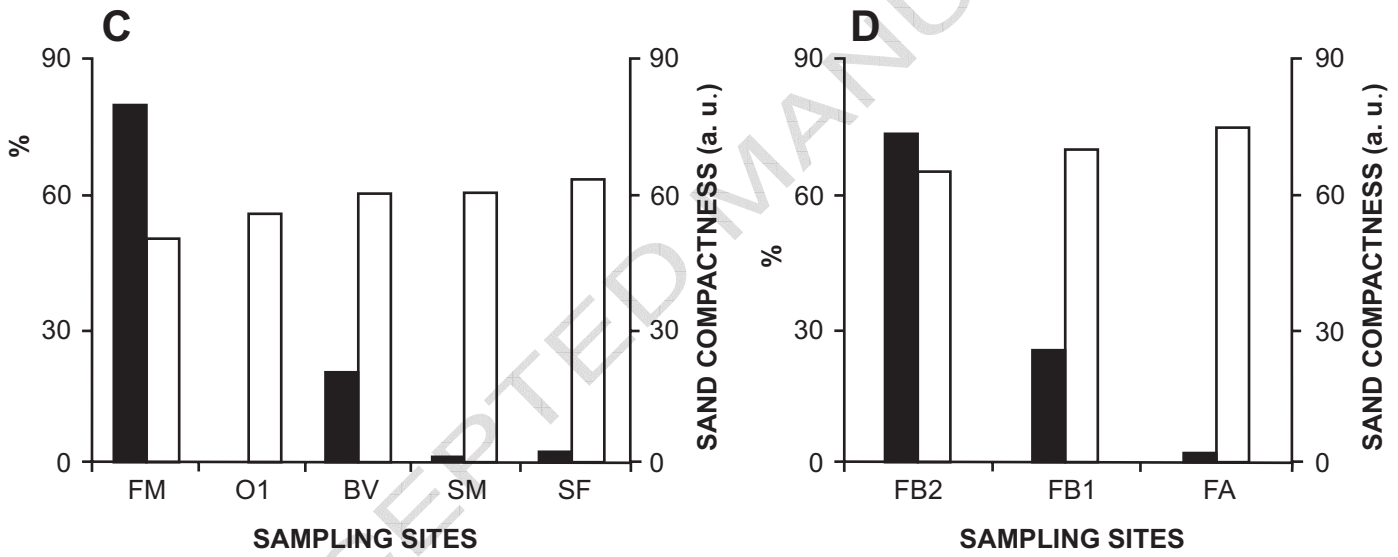


Figure 4

GRANULOMETRY



SAND COMPACTNESS



ORGANIC CARBON

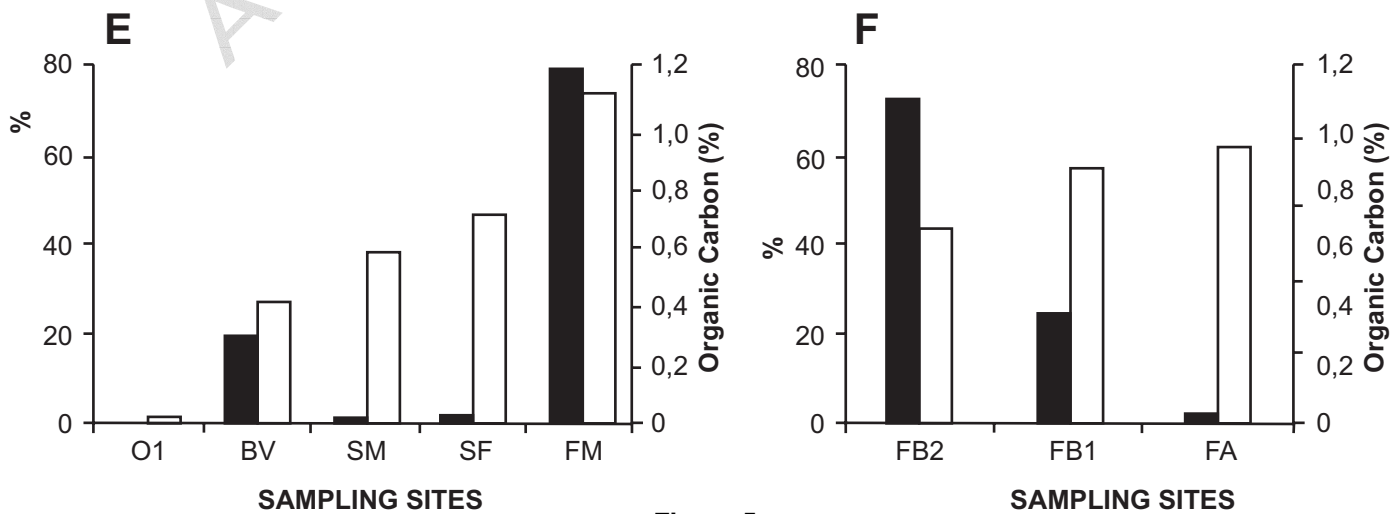


Figure 5

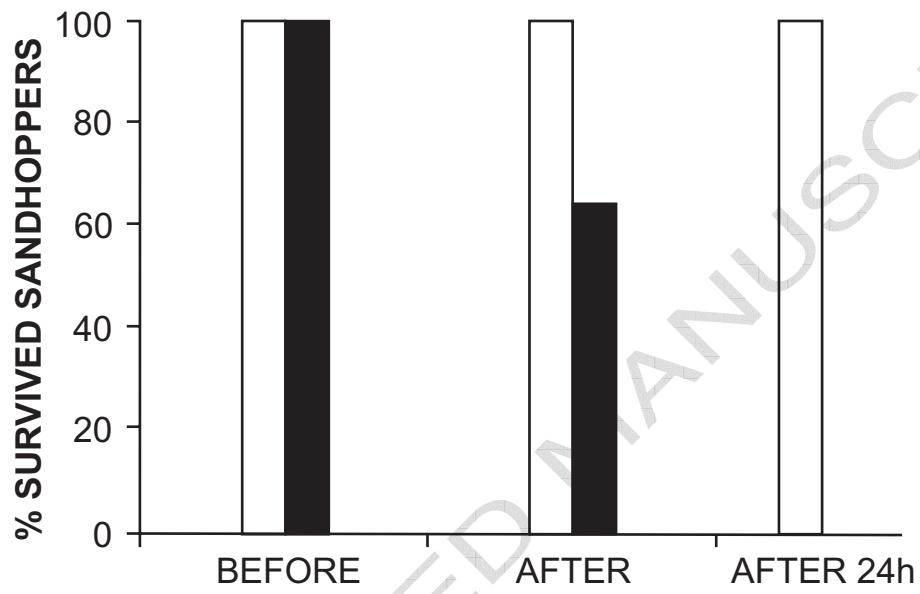


Figure 6

Sampling sites		June	July	August	September
FM	sandhoppers	348.3±59	709±332	438±466	256±325
	swimmers	1.3±1.5	4±2	3.6±4.4	1.66±1.5
BV	sandhoppers	204±85	174±40	184.6±104	158±192
	swimmers	10±13	6±2.6	6.6±9	1.3±1.5
SF	sandhoppers	21±31	15±15	2.3±4	16.3±18
	swimmers	18±19	25.6±15	18.6±12	4.3±5
SM	sandhoppers	8±12	1.33±1.5	0	0
	swimmers	82±70	146±137	70±21.2	16.6±13.5
O1	sandhoppers	0	0	0	0
	swimmers	196±190	310±134	175±76	28.6±17.8

Table

Sampling sites	Mean sand grain diameter (mm)	Standard deviation	Skewness	Kurtosis
FM	1.605	0.471	-0.012	0.503
BV	1.324	0.507	0.247	0.494
SF	1.751	0.506	0.180	0.598
SM	1.669	0.469	0.051	0.582
O1	1.484	0.486	0.170	0.543
FB2	1.738	0.436	0.234	0.631
FB1	2.166	0.435	-0.043	0.511
FA	2.032	0.489	0.065	0.552

Table