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## Connecting organic to mineral: How the physiological state of an ecosystem-engineer is linked to its habitat structure

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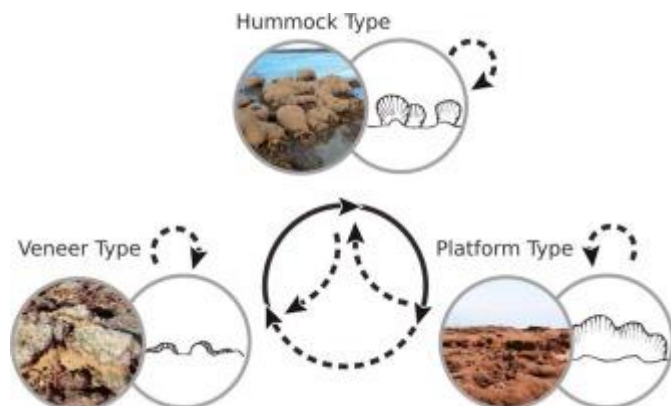
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### Abstract :

The honeycomb worm *Sabellaria alveolata* is capable of building extensive bioconstructions, including what are currently considered Europe's largest biogenic reefs. The size and volume of these bioconstructions, however, vary greatly, such that not all habitats engineered by *S. alveolata* may be easily identified as reefs. Given that European environmental legislation protects marine habitats that are classified as "reefs", it is important to identify a clear set of definition criteria. Furthermore, quantifiable and unequivocal criteria are also needed to evaluate the ecological (health) state of these reefs, in order to best monitor and protect them. Here we propose new terminology to describe the physical appearance of these bioconstructions and attempt to link these physical criteria to the physiological state of the tube-building polychaete. We tested whether a bioconstruction displaying outward signs of growth is built by "healthy" worms devoid of physiological stress by analysing three macromolecules (carbohydrates, proteins, lipids), four polar lipid fatty acids, six neutral lipid fatty acid markers and three metabolic enzymes (citrate synthase, catalase and superoxide dismutase). The worms were sampled in bioconstructions of different "Type" (veneer vs. hummock), "Phase" (progradation vs. retrogradation), and "Shore Level" (high shore vs. low shore) at Champeaux in Mont-Saint-Michel Bay, France. Our results show that worms sampled in retrograding reefs (i.e. displaying signs of erosion and colonisation by epibionts such as oysters or mussels), were less physiologically stressed than worms sampled in prograding bioconstructions, possibly due to lower intraspecific competition and hence greater food availability. We therefore suggest management measures should encompass the whole mosaic of biogenic construction Types and Phases. We propose the inclusion of the polar lipid fatty acid arachidonic acid, in combination with the activity of two metabolic enzymes, citrate synthase and superoxide dismutase, as the three key biochemical markers to consider for quantitative information on the physiological state of this particular ecosystem engineer. Our results also revealed the influence of both sex and size on fatty acid and enzyme levels, highlighting the importance of taking into account both these variables when sampling and subsequently pooling individuals by sex and size category for laboratory analyses. Once seasonal and site variation have been addressed, these biochemical indicators could be examined in parallel with *S. alveolata* bioconstruction physical criteria as part of a European-wide protocol for monitoring ecological status in this potential reef habitat.

## Graphical abstract



## Highlights

► Biochemical markers can be informative for monitoring bioengineered habitats. ► Management measures should cover multiple bioconstruction types and phases. ► Physiological distress is not correlated with retrograding bioconstructions. ► Worms in retrograding bioconstructions have a higher quantity of available food. ► Three biochemical markers stand out as relevant physiological state descriptors.

**Keywords** : Biochemical indicators, Health, Ecological status, *Sabellaria alveolata*, Biogenic reef, Engineer species

## 56 **1. Introduction**

57 Biogenic reefs are among the most biologically diverse and functionally important habitats on  
58 Earth (Goldberg, 2013). Their physical structure is known to provide numerous provisioning  
59 and regulating services, such as unique habitat provision and coastal protection (Hattam et al.,  
60 2015). Tropical coral reefs are often the first image that springs to mind upon hearing the term  
61 “reef”, and are the subject of enormous literature. Scleractinian corals, however, are only one  
62 of many marine taxa capable of building biogenic reefs, which can be defined as follows:  
63 “*solid, massive structures which are created by accumulations of organisms*” and “*clearly*  
64 *forming a substantial, discrete community or habitat which is very different from the*  
65 *surrounding seabed*” (Holt et al., 1998). In temperate waters, shellfish and tube-dwelling  
66 polychaetes also fall under this definition (Bartol et al., 1999; Dubois et al., 2006).

67 The term “healthy reefs” is ubiquitous throughout the literature on marine conservation;  
68 healthy reefs are often the focus of protection efforts (Abelson et al., 2017). Yet when it  
69 comes to assessing reef health status, the metrics most commonly described assess either  
70 ecological (*i.e.* species richness and presence of species of interest), or landscape  
71 characteristics (*i.e.* elevation, extent, coverage). It is unknown whether these assessments are  
72 indicative of the health of the engineering organism itself.

73 Reef-building sabellariid worms are ubiquitous globally in both intertidal and shallow subtidal  
74 zones. The species responsible for building what are currently considered as Europe’s largest  
75 biogenic reefs (Gruet, 1986) is the honeycomb worm *Sabellaria alveolata* (Linnaeus, 1767).  
76 This sedentary colonial polychaete creates tubes of coarse sand grains and shell fragments  
77 cemented together; dense aggregations of which may be regarded as reefs (Holt et al., 1998).  
78 This Lusitanian species is widely distributed from southwest Scotland to Morocco where it  
79 inhabits the low- to mid-shore (Gruet, 1986; Dubois et al., 2002). As an ecosystem engineer,  
80 *S. alveolata* generates small to large scale topographic complexity, creating numerous spatial  
81 and trophic niches for other species to colonise (Dubois et al., 2002; 2006; Dubois and  
82 Colombo 2014; Jones et al., 2018). Their bioconstructions buffer physical and chemical  
83 stresses, protect from predators and competitors, and alter resource availability (Porrás et al.,  
84 1996). Consequently, these bioconstructions host highly diverse and unique communities,  
85 composed of species originating from hard, muddy and sandy substrates, in addition to both  
86 subtidal and intertidal habitats (Dubois et al., 2002; 2006; Schimmenti et al., 2015), and are  
87 broadly considered as local hotspots of biodiversity (Jones et al., 2018).

88 Honeycomb worm bioconstructions constitute a highly dynamic habitat subject to numerous  
89 natural (*e.g.* cold winters or storms) and anthropogenic disturbances (*e.g.* trampling,  
90 harvesting, shellfish farming, coastal development) (Dubois et al., 2002; Firth et al. 2015;

91 Plicanti et al., 2016). These bioconstructions may take on three main structural types (see *e.g.*  
92 Cunningham, 1984 and Holt et al., 1998, Fig. 1). Gruet (1982) described a cycle whereby a  
93 bioconstruction evolves from (1) “veneers” in which the tubes overlap and lie at an acute  
94 angle to the substratum, to (2) “hummocks” in which the tubes radiate out from the initial  
95 settlement point before reaching (3) “platforms” formed of extensive areas of hummocks  
96 fused together. In the majority of locations throughout Europe, however, neither the  
97 “hummock” nor “platform” type is ever reached. Any one of these bioconstruction types can  
98 display outward signs of being in a “progradation” or “retrogradation” phase (Figure 1a).  
99 Gruet (1982) was the first to refer to *S. alveolata* reef phases, which he referred to as  
100 “growth” and “destruction”. Here we propose new terminology for *S. alveolata*  
101 bioconstruction development. The engineered structure is constantly in a delicate balance  
102 between these two phases, and can therefore display some or all of the characteristics listed in  
103 Figure 1 B. Patches can undergo cyclic or erratic changes whereby they prograde or  
104 retrograde either partially or totally through resettlement, as *S. alveolata* larvae, as with all  
105 sabellariid species, preferentially settle on conspecific adult tubes (Pawlik, 1986).

106

107 Currently there is no single definition or guidance of what constitutes a *S. alveolata* “reef”.  
108 Far from being a semantic dispute, this has far-reaching implications in terms of management  
109 and conservation, as throughout the majority of its distribution (*i.e.* Europe) the sole  
110 legislative instrument affording any protection is the Habitats Directive (Council Directive  
111 92/43/EEC), which only protects the “reef” form of biogenic constructions. A “reefiness”  
112 scoring system in the context of the Habitats Directive was developed by Hendrick and  
113 Foster-Smith (2006) for subtidal *Sabellaria spinulosa* reefs, based on a series of physical,  
114 biological and temporal characteristics weighted according to data quality of and perceived

115 importance of each feature. Desroy et al. (2011) developed a Health Status Index for *S.*  
116 *alveolata* bioconstructions at the Bay of Mont-Saint-Michel, based on fragmentation,  
117 proportion of different bioconstruction morphological types and coverage by three key  
118 epibionts (*i.e.* oysters, *Magallana* (formerly *Crassostrea*) *gigas*, mussels, *Mytilus* spp., and  
119 green macroalgae, *Ulva* spp.). Existing rapid assessments of intertidal *S. alveolata* “quality”  
120 (*i.e.* Cunningham, 1984; Firth et al., 2015) are based on visual evaluations of the  
121 bioconstructions, and do not consider environmental characteristics of the site. Whilst all of  
122 these scoring indices are very useful, they may not easily translate beyond the species or  
123 biogeographic regions that they were developed for. Due to differences in morphology  
124 between the two species, the “reefiness” score for *S. spinulosa* developed by Hendrick and  
125 Foster-Smith (2006) is more helpful as a means of comparing the relative values of two  
126 different areas of *S. spinulosa* reef. The Health Status Index developed by Desroy et al. (2011)  
127 is only applicable in areas where *S. alveolata* bioconstructions reach the platform type and  
128 become colonised by *M. gigas* or *Mytilus* spp., thus restricting its application. Furthermore,  
129 not only do both of these indices require a considerable amount of field and laboratory work  
130 with numerous field experts, they also rely entirely on the physical looking-aspect of the  
131 bioconstruction. For example, muddy and fragmented bioconstruction patches have a low  
132 score on Desroy et al. (2011) health scale, disregarding the actual physiological state of the  
133 worm.. The main objective of the present study was to develop a generic tool that would be  
134 applicable across the entire geographic range of *S. alveolata*, able to help linking the physical  
135 state of the bioconstructions with the physiological state of the individuals.

136

137 Biochemical proxies may provide generic health indicators well suited for *S. alveolata*. Cell  
138 health and survival rely on a series of biochemical fluxes and reactions that are highly  
139 conserved among species and biogeographic regions (Hochachka and Somero, 2002).

140 Therefore, biochemical indicators can be used as a snapshot of the physiological condition of  
141 the individual at the time it was sampled (Fraser, 1989; Dahlhoff, 2004), and could potentially  
142 have similar applicability across a variety of taxa. In order to understand how the  
143 physiological condition of *S. alveolata* ties in with their bioconstruction structure (*i.e.* type,  
144 phase and shore level), we focused on a suite of metabolic parameters that reflect several key  
145 physiological processes.

146

147 Information on the organic macromolecules of a species is fundamental to understanding its  
148 biochemical characteristics. Carbohydrates and neutral lipids constitute major energy reserves  
149 for fuelling growth, reproduction, and defence against stressors in many marine invertebrates  
150 (*e.g.* Gallagher et al., 1986; Berthelin et al., 2000; Rivest et al., 2017). Glycogen is the primary  
151 polysaccharide (polymeric carbohydrate) in annelids (Scheer, 1969) and has long been  
152 recognised as the principal energy reserve in juvenile and adult bivalves (Lucas and Beninger,  
153 1985). It serves both as an energy reserve under unfavourable environmental conditions, and  
154 also for the formation of gametes (Gabbott, 1975). Quantifying glycogen levels may therefore  
155 provide an indication of the level of energy reserves in *S. alveolata*.

156

157 Fatty acids, which are key constituents of the lipid compartment, vary with environmental  
158 factors such as temperature (*e.g.* Pernet et al., 2007) or salinity (Fuhrmann et al., 2018),  
159 trophic sources (Winder et al., 2017) and life history stage (*e.g.* Soudant et al., 1999;  
160 Lourenço et al., 2017). On one hand, the fatty acid composition of neutral lipids, which  
161 generally consists of triglycerides, reflects the fatty acid profile of the food consumed, thus  
162 revealing useful information about quality and assimilation of trophic sources (Dalsgaard,  
163 2003). On the other hand, the fatty acid composition of polar lipids, which mainly originate  
164 from cell membranes (phospholipids), is altered to enable physiological adaptation of



165 organisms to their physical environment (Hazel and Williams, 1990; Hochachka and Somero,  
166 2002). The best example of this is the remodelling of membrane lipids by ectothermic  
167 animals, including *S. alveolata*, to counteract the effect of temperature on membrane fluidity  
168 (Hazel, 1995; Muir et al., 2016). Some fatty acids are particularly informative. The fatty acid  
169 20:4n-6 (arachidonic acid) is a precursor of hormones involved in stressful or energetically  
170 expensive situations, namely gametogenesis and spawning (Osada, Nishikawa and Nomura,  
171 1989), stimulation of immune functions in marine invertebrates (Delaporte, 2003) and  
172 acclimation to increasing seawater temperatures in *S. alveolata* (Muir et al., 2016). Therefore,  
173 fatty acid composition acts as a good stress bioindicator in marine organisms.

174

175 Metabolism is the biological processing of energy and materials through a series of  
176 biochemical reactions catalysed by enzymes (Brown et al., 2004). Metabolic enzymes are  
177 proteins which help maintain physiological homeostasis. Citrate synthase is a central enzyme  
178 in the process of sugar oxidation involved in adenosine triphosphate (ATP) generation. It is  
179 the first step of the citric acid or Krebs cycle, consisting of a series of chemical reactions  
180 which generate energy through the oxidation of acetyl-Coenzyme A derived from  
181 carbohydrates, lipids and proteins. Citrate synthase activity (CS) is correlated with respiration  
182 rate in marine invertebrates and can be used as indicator of oxidative stress (Dahlhoff et al.,  
183 2002). Reactive oxygen species (ROS) are generated through cell respiration and their  
184 production is exacerbated by environmental stressors such as contaminants, pathogens and  
185 dietary restrictions (*e.g.* Abele and Puntarulo, 2004 for review). Accumulation of ROS in  
186 aerobic cells can result in oxidative stress in the host (Lesser, 2006) which is normally  
187 prevented by an enzymatic antioxidant system. Studies have highlighted the importance of the  
188 enzymes superoxide dismutase (SOD) and catalase (CAT) in the prevention of tissue damage  
189 from oxidative stress in marine invertebrates (Abele and Puntarulo, 2004 for review).

190

191 The overall objective of this study was to investigate the relationship between the outward  
192 structural appearance of the bioconstruction and the physiology of the resident individuals.  
193 From a practical standpoint, we tested the effect of the physical appearance of the  
194 bioconstructions in terms of their structural Type (vener vs. hummock, but not platform due  
195 to this type being absent from the majority of locations), Phase (progradation vs.  
196 retrogradation) and shore level (high vs. low-shore) on several well-known biochemical  
197 indicators of health. Key macromolecules, enzyme activity and fatty acid composition of  
198 neutral and polar lipids may change between different bioconstruction phases of growth and  
199 deterioration and are likely to modulate the individual's response to environmental stressors.

200

## 201 **2. Materials and Methods**

### 202 **2.1 Study location: Champeaux Reef**

203 Our study took place in the Bay of Mont-Saint-Michel (north-western France), a megatidal  
204 (>14m) ecosystem with one of the highest maximum spring tidal range values in the world  
205 (Levoy et al., 2017). It is home to the largest and most extensive biogenic constructions in  
206 Europe, namely the Saint-Anne reef (2.25 km<sup>2</sup>) and the Champeaux reef (0.29 km<sup>2</sup>) (Desroy  
207 et al., 2011). The current study focused on the Champeaux reef affixed to rocky substrate in  
208 the upper intertidal zone, situated in the southeastern part of the Bay (48.7318, 01.5520;  
209 Figure 2). The tidal amplitude in a megatidal regime implies that the water column is very  
210 well mixed. The surrounding substrate is known as "*tangue*", a heterolithic sediment  
211 displaying an alternate structure of sandy and silty-muddy beds which represent the deposit of  
212 each semi-diurnal tidal cycle (Tessier, 1993).

213 **2.2 Sampling design**

214 Twelve patches of *S. alveolata* were sampled on the bioconstruction during low water on the  
215 22<sup>nd</sup> February 2016. Five individual worms were extracted from each patch of either veneer or  
216 hummock type (Table 1). For hummocks, the distinction was made between formations  
217 presenting outward signs of either progradation or retrogradation. Most treatments were well  
218 interspersed over the study area, but within ~50 m from each other. Although we would have  
219 ideally wished to sample all shore heights and phases for all types, our study location only  
220 allowed for prograding hummocks to be sampled both on the high and low shore, whilst  
221 retrograding hummocks were only present in the eastern part of the study site (Figure 2).

222

223 Small clumps of tubes were broken off, and five females were gently extracted from their  
224 tubes for each sampling point. In addition, five males were sampled from one low-shore  
225 hummock patch located in the centre of the reef. Worms were randomly sampled within  
226 mature individuals. Maturation stage was assessed by visual examination of the extracted  
227 worms. Unspent (*i.e.* those that had not shed their gametes) worms are creamy white for  
228 males and purplish/rose-violet for females, while spent worms are thin-bodied brownish (see  
229 Wilson, 1971, Gruet and Lassus, 1983, Wilson, 1968 cited in Culloty et al., 2010). All  
230 sampled worms were placed in cryotubes and immediately flash frozen in liquid nitrogen *in*  
231 *situ* before they could start releasing their gametes. Samples were then long-term stored at -  
232 80°C until laboratory analyses.

233

234 **Table 1.** Summary of the sampling design. Abbreviations: nc, not considered for analysis; F,  
235 Female; M, Male.

---

Bioconstruction	Shore level	Sex	Patch	Number of	Code
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Type	Phase		individuals				
Hummock	Retrogradation	nc	F	1	5	HR1	
Hummock	Retrogradation	nc	F	2	5	HR2	
Hummock	Retrogradation	nc	F	3	5	HR3	
Hummock	Progradation	High	F	1	5	HPHs1	
Hummock	Progradation	High	F	2	5	HPHs2	
Hummock	Progradation	High	F	3	5	HPHs3	
Hummock	Progradation	Low	F	1	5	HPLs1	
Hummock	Progradation	Low	F & M	2	5 & 3	HPLs2	
Hummock	Progradation	Low	F	3	5	HPLs3	
Veneer	nc	nc	F	1	5	V1	
Veneer	nc	nc	F	2	5	V2	
Veneer	nc	nc	F	3	4	V3	

## 236 2.3 Laboratory analyses

237 Individual worms were weighed and ice-cold milliQ water was added at ¼ mass volume ratio.  
238 Then, samples were grinded and homogenised 2×20 seconds at 4.5 m sec<sup>-1</sup> using the  
239 FastPrep-24™ 5G Instrument (MP Biomedicals SARL, Illkirch, France). Tissue samples were  
240 aliquoted in one tube containing 100-200 µL for lipid analyses and in six tubes containing 180  
241 µL for carbohydrate and protein extraction.

### 242 2.3.1 Carbohydrates

243 An aliquot of 180 µl of tissue sample was used for determination of total carbohydrate  
244 concentrations. Briefly, samples were diluted 10 times by addition of 820 µL MilliQ water.  
245 Carbohydrate concentrations were determined by colorimetric method according to DuBois  
246 (1956). Then, samples (250 µL) were mixed with phenol (0.5 ml, 5% m/v) and sulfuric acid  
247 (2.5 ml, 98%), and incubated for 40 min. Absorbance was read at 490 nm with a UV 941  
248 spectrophotometer (Kontron instruments, San Diego, California, USA). Carbohydrate

249 concentrations were determined using a standard calibration curve and expressed as mg of  
250 carbohydrates per g of wet weight.

## 251 **2.3.2 Lipids**

### 252 **2.3.2.1 Extraction**

253 One aliquot tube of 180 $\mu$ l was used for determination of fatty acid profiles of neutral and  
254 polar lipids. The sample was transferred into a 6 mL glass vial. Lipids were extracted  
255 according to Bligh and Dyer (1959). A mixture of CHCl<sub>3</sub>:MeOH 1:2 (v/v, 750  $\mu$ L) was added  
256 to the sample. Then, the sample was vortexed before adding pure CHCl<sub>3</sub> (250  $\mu$ L), vortexed  
257 again, diluted with MilliQ water (250  $\mu$ L), vortexed again, and centrifuged at 3000 rpm for 5  
258 minutes. The lower organic phase was transferred into another clean 2-mL glass vial. The  
259 remaining aqueous phase was washed with 500  $\mu$ L CHCl<sub>3</sub>, vortexed, and centrifuged again.  
260 The lower phase was recovered, pooled with the first one and evaporated under a nitrogen  
261 flow. The sample was stored at -20°C in 1 mL of CHCl<sub>3</sub>:MeOH 98:2 (v/v).

### 262 **2.3.2.2 Neutral and Polar Lipid Separation**

263 Subsamples (250  $\mu$ L) were then placed on the top of a silica gel micro column (30 $\times$ 5 mm  
264 internal diameter; Kieselgel; 70–230 mesh (Merck, Lyon, France); previously heated to  
265 450°C and deactivated with 5% water) (Marty et al., 1992). Neutral lipids were eluted with 10  
266 ml of CHCl<sub>3</sub>:MeOH (98:2, v/v) and the polar lipids were recovered with 15 ml of MeOH. A  
267 known amount of tricosanoic acid (23:0) was added to both fractions as an internal standard.  
268 The lipid fractions were evaporated to dryness under nitrogen, re-suspended in CHCl<sub>3</sub>:MeOH  
269 2:1 (v/v) before transesterification.

### 270 **2.3.2.3 Transesterification**

271 Neutral and polar lipids were transesterified at 100°C for 10 min with 1 mL of boron  
272 trifluoride-methanol (12% MeOH) (Metcalf and Schmitz, 1961). This transesterification  
273 produces fatty acid methyl esters (FAME) from the fatty acid esterified at the sn-1 and sn-2  
274 position of diacylphospholipids, and the sn-2 position of plasmalogen phospholipids. It also  
275 produces dimethyl acetals (DMA) from the alkenyl chains at the sn-1 position of  
276 plasmalogens (Morrison and Smith, 1964). FAME and DMA were analysed in a HP6890 gas-  
277 chromatography system (Hewlett-Packard) equipped with a DB-Wax capillary column  
278 (30 m × 0.25 mm; 0.25 µm film thickness; Agilent technologies). Peaks were analysed by  
279 comparison with those of a standard 37 component FAME mix (Supelco® 37, Merck)  
280 together with other known FAME mixes from marine invertebrates. Each fatty acid was  
281 expressed as the peak area percentage of the total fatty acid content. Total DMA was used as  
282 an indicator of the plasmalogen level.

283 The fatty acid trophic markers investigated in this study were the ratio of 16:1n-7/16:0 and  
284 16:4n-1 both of which indicate the contribution of diatoms to the diet; the ratio of 22:6n-  
285 3/20:5n-3 which is used as an indicator of dinoflagellate contribution relative to diatoms, all  
286 of the sum of 18:2n-6 and 18:3n-3, which is generally considered as a marker of terrestrial  
287 inputs; the ratio of 18:1n-9/18:1n-7, which is generally used as an indicator of carnivory; the  
288 ratio of polyunsaturated/saturated fatty acid (PUFA/SFA), which is an indicator of food  
289 freshness; and the sum of iso- and anteiso-branched chain fatty acids and unbranched 15:0  
290 and 17:0, which reflects the contribution of bacteria to the organic matter. These fatty acid  
291 food web markers are routinely used in trophic ecology (Dalsgaard, 2003). The ratio of  
292 neutral to polar lipid content was also calculated, as this proxy reflects the relative

293 contribution of reserve to structural lipids and is used as a nutritional condition index that is  
294 scaled to body size (Hentschel, 1998).

### 295 **2.3.3. Enzymes**

#### 296 **2.3.3.1. Protein extraction and quantification**

297 Tissue samples of 150µl were diluted by 2/3 in ice-cold lysis buffer solution and  
298 homogenized with a Polytron® PT 2500 E (Kinematica, Luzernerstrasse, Switzerland). The  
299 buffer solution was made of 150 mM NaCl, 10 mM Tris, 1 mM EDTA, 1 mM EGTA, 1%  
300 Triton X-100, 0.5% Igepal, 1 tablet of complete EDTA free protease inhibitor cocktail (Roche  
301 Diagnostics, Risch-Rotkreuz, Switzerland) in 25 ml of buffer, phosphatase inhibitor cocktail  
302 III (Merck KGaA, Darmstadt, Germany) all at pH 7.4 (Le Foll et al., 2006). Homogenates  
303 were incubated for 1 hour before being centrifuged twice at 4000 rpm for 1 hour at 4°C and at  
304 11700 rpm for 45 min at 4°C to eliminate the lipid fraction of the samples, using GR412 and  
305 MR22 Jouan centrifuges (Thermo Scientific, Waltham MA, USA), respectively. The resulting  
306 supernatants were aliquoted and stored at -80°C until protein quantification and enzyme  
307 assays.

308

309 To determine total protein concentration, an aliquot of protein extract was diluted by 1/10<sup>th</sup>  
310 and quantified according to Lowry et al. (1951) using the *DC<sub>tm</sub>* protein assay kit (Bio-Rad,  
311 Hercules, California, USA). Absorbance was read at 750 nm and protein concentrations were  
312 determined by comparison with a calibration curve of Bovine Serum Albumin provided with  
313 the kit. Results were expressed as mg of proteins per g of dry tissue weight.

### 314 **2.3.3.1 Citrate Synthase**

315 Enzyme assays were performed in triplicate at room temperature and enzyme activities were  
316 expressed and related to the total protein concentration for each sample.

317 Citrate synthase activity (CS; EC 4.1.3.7) was assayed at room temperature according to  
318 Childress and Somero (1979). Protein extract (20  $\mu$ L) was added in wells containing an assay  
319 buffer solution (160  $\mu$ L) which consisted of 100 mM Tris-HCl, 0.2 mM acetyl-coenzyme A,  
320 0.1 mM 5, 5' -dithio-bis-[2-nitrobenzoic] acid (DTNB). The reaction was initiated by adding  
321 oxaloacetate (0.5 mM; 20  $\mu$ L). Absorbance was recorded for 10 min at 412 nm using a  
322 Synergy HT microplate reader (BioTek, Winooski VT, USA). Results were expressed in mU  
323  $\text{mg}^{-1}$  protein, where 1 U is the amount of enzyme to catalyze 1  $\mu$ mole of TNB per minute  
324 (using  $\epsilon_{\text{TNB},412} = 13.6 \text{ mM}^{-1} \text{ cm}^{-1}$ ).

### 325 **2.3.3.2 Superoxide Dismutase**

326 Total superoxide dismutase activity (SOD; EC 1.15.1.1) was determined using an assay kit  
327 (Merck KGaA, Darmstadt, Germany), following the manufacturer's instruction. Superoxide  
328 dismutase activity (SOD) was measured by adding 200 $\mu$ L of Water-Soluble Tetrazolium salt  
329 (WST-1) to 15 $\mu$ L of total protein lysates 10 times diluted, and the reaction was initiated by  
330 adding 20 $\mu$ L of xanthine oxidase (XO) and xanthine mix. After a 20 min incubation at 37°C,  
331 absorbance was read at 450nm using a Synergy HT microplate reader (BioTek, Winooski VT,  
332 USA). SOD is quantified by comparing the decrease in the colour development at 450nm to a  
333 standard inhibition curve, performed using SOD from bovine erythrocytes. Results were  
334 expressed in units per mg of protein (U/mg), where 1 U of SOD is the amount of enzyme  
335 necessary to inhibit by 50% the xanthine/XO complex formation.



### 336 2.3.3.3 Catalase

337 Catalase activity (CAT; EC 1.11.1.6) was assessed at room temperature following Aebi  
338 (1984). Briefly, 5  $\mu\text{L}$  of 10 times diluted protein supernatant were added to 195  $\mu\text{L}$  of  
339 hydrogen peroxide solution (10 mM) to initiate the reaction. Absorbance was immediately  
340 recorded for every 15 s for 4 min using a Synergy HT microplate reader (BioTek, Winooski  
341 VT, USA). CAT is expressed in U/mg protein where 1 U is the amount of enzyme necessary  
342 for catalysing 1  $\mu\text{mole}$  of  $\text{H}_2\text{O}_2$  per min (using  $\epsilon_{\text{H}_2\text{O}_2}$ ,  $39.4 \text{ mM}^{-1} \text{ cm}^{-1}$ ).

### 343 2.4. Statistical analyses

344 Mixed design analyses of covariance (ANCOVA) were used to compare lipid, carbohydrate,  
345 and protein contents, enzyme activities and relative fatty acid concentration of the *S. alveolata*  
346 samples among the different bioconstruction types, phases and shore level. In the model, the  
347 random factor was the patch where the samples were taken and the covariate was individual  
348 worm mass (*i.e.* wet weight measures for 59 individual females). The individual worm mass  
349 did not vary with bioconstruction characteristics (ANOVA  $F$ -test=2.35,  $p=0.148$ ) and can  
350 therefore be used as an independent factor. The categorical fixed variables were the four  
351 combinations of bioconstruction types and phases: veneer (V), retrograding hummock (HR)  
352 and prograding hummock located either on the high-shore (HPHs) or low-shore (HPLs).  
353 Interactions between bioconstruction characteristics and worm mass were systematically not  
354 significant and therefore omitted from the model (Table 2). When  $F$ -tests were significant the  
355 following *a priori* null hypotheses ( $H_0$ ) were tested using contrasts:

$$H_{0_1}: \mu_V = \frac{\mu_{HR} + \mu_{HPHS} + \mu_{HPLS}}{3}$$

$$H_{0_2}: \mu_{HR} = \frac{\mu_{HPHS} + \mu_{HPLS}}{2}$$

$$H0_3: \mu_{HPHS} = \mu_{HPLS}$$

356 To compare males and females, the unequal variance *T*-test was used. The normality of  
 357 residuals and homogeneity of variances were investigated using Box-Cox transformations  
 358 (Box and Cox, 1964). When necessary data were log-transformed. All statistical tests were  
 359 performed with SAS software (SAS 9.4, Carry NC, USA).

360 **Table 2.** Summary of the mixed analyses of covariance (ANCOVA) model used for  
 361 comparing females. df = degrees of freedom

<b>Sources of variation</b>	<b>df</b>
<i>Main-plot analysis</i>	
Bioconstruction characteristics	3
H0 <sub>1</sub> : Veneer (V) = Hummock (H)	1
H0 <sub>2</sub> : Retrograding H (HR) = Prograding H (HP)	1
H0 <sub>3</sub> : HP High-shore (HPHs) = HP Low-shore (HPLs)	1
Error a: Patch (Bioconstruction characteristics)	8
<i>Subplot analysis</i>	
Individual worm mass	1
Error b: Individual worm mass × Patch (Bioconstruction characteristics)	47
Total	59

362

### 363 **3. Results**

364 We investigated the effect of bioconstruction characteristics, worm mass and sex on 16  
 365 different parameters grouped into four categories (Figures 3 to 6). We report that

366 bioconstruction characteristics were associated with variations in three out of four indicator  
367 categories, whereas both individual mass and sex drove differences in all four categories.

### 368 **3.1 Organic macromolecules**

369 There was a significant relationship between the neutral:polar lipid ratio and bioconstruction  
370 characteristics (Fig. 3c), where the two bioconstruction phases contrasted significantly  
371 ( $F_{1,8}=20.1$ ,  $p=0.002$ ), with a higher neutral:polar lipid ratio found in the retrogradation phase.  
372 Individual wet weight was negatively correlated with both carbohydrate and protein  
373 concentration, and positively correlated with neutral:polar lipid ratio (Fig.3d-f). Females had a  
374 neutral:polar lipid ratio that was 5.9 times higher than males (Fig.3i), however sex had no  
375 effect on either proteins or carbohydrates (Fig.3g and h).

### 376 **3.2 Fatty acids**

#### 377 **3.2.1 Polar lipids**

378 There was a significant effect of bioconstruction characteristics on both gadoleic (20:1n-11)  
379 and arachidonic (20:4n-6) acid after controlling for individual worm mass. Gadoleic acid  
380 varied with bioconstruction type and was significantly higher in worms sampled in hummocks  
381 than in worms from veneers ( $F_{1,8}=12.0$ ,  $p=0.009$ ) (Fig.4a). Arachidonic acid levels varied  
382 with bioconstruction phase and were significantly lower in retrograding hummocks ( $F_{1,8}=7.8$ ,  
383  $p=0.024$ ) (Fig.4b). 20:4n-6 levels were near-significantly lower on the low shore ( $F_{1,8}=4.8$ ,  
384  $p=0.059$ ) at 1.9%, compared to 2.2% on the high shore. Both eicosapentaenoic acid (20:5n-3)  
385 and docosahexaenoic acid (22:6n-3) were not influenced by bioconstruction characteristics  
386 (Fig. 4c and d). 22:6n-3 was the only polar lipid fatty acid to be significantly negatively  
387 correlated with individual wet weight (Fig.4h). Sex clearly influenced levels of 20:1n-11 and  
388 22:6n-3 content but had no effect on the other markers (Fig.4i and l); the former is present in

389 greater quantity in females than in males whereas the latter is present in greater quantity in  
390 males than in females.

### 391 **3.2.2 Neutral lipids**

392 Fatty acid composition in neutral lipids was not influenced by bioconstruction characteristics  
393 (Fig. 5a-f). With the exception of bacterial and carnivory markers, all neutral lipids were  
394 positively influenced by individual wet weight (Fig. 5gh and kl). A strong difference between  
395 male and female was observed for all trophic markers, with female worms exhibiting higher  
396 values for all markers except for carnivory, where males have 18:1n-9/18:1n-7 levels twice as  
397 high as those found in females (Fig. 5o). The 16:1n-7/16:0 ratio (Fig. 5a), which is used as a  
398 diatom tracer, was corroborated by a second diatom tracer, 16:4n-1 (File S1), whose  
399 concentration was significantly influenced by both individual wet weight and sex.

### 400 **3.2 Enzyme assays**

401 Citrate synthase activity (CS) was significantly affected by bioconstruction characteristics  
402 (Fig. 6a); average CS was near significantly higher in worms sampled in hummocks than in  
403 veneers ( $p=0.054$ ), and twice as high in worms sampled in the retrogradation phase compared  
404 to the progradation phase ( $F_{1,8}=10.1$ ,  $p=0.013$ ). Although superoxide dismutase activity  
405 (SOD) was not significantly influenced by bioconstruction characteristics (Fig. 6), SOD  
406 positively correlated with CS (File S1,  $CS=0.95+3.17\times SOD$ ,  $r^2=0.400$   $p<0.001$ ). Individual  
407 wet weight was negatively correlated with CS, but not with catalase activity (CAT) or SOD  
408 (Fig.6). Sex clearly influenced CS activity but had no effect on either CAT or SOD (Fig.3cfi).  
409 Mean CS was 3.8 times higher in males than in females (Fig.6c). Relationships among all  
410 variables measured in our study were represented in a principal component analysis biplot  
411 (File S1).

#### 412 **4. Discussion**

413 Our study revealed that a retrograding *Sabellaria alveolata* bioconstruction does not  
414 necessarily equate with reserve-depleted worms. Indeed, carbohydrate levels did not vary  
415 between retrograding and prograding bioconstructions, and the ratio of neutral:polar lipids  
416 was in fact higher in the retrogradation phase. Neutral lipids are essential energy reserves for  
417 sustaining early life stages and play a key role in settlement, habitat selectivity and  
418 recruitment in marine invertebrates (*e.g.* Tremblay et al., 2007). Also, higher levels of  
419 energetic reserves are associated with a better ability to cope with stressful situations such as  
420 pathogen resistance (Lochmiller and Deerenberg 2000, Pernet et al., 2014, Ellis et al., 2011).  
421 It is therefore likely that worms living in retrograding reefs are better equipped to face  
422 stressful situations.

423

424 We also found that levels of 20:4n-6 in the polar lipids of worms sampled in the  
425 retrogradation phase were lower than in the progradation phase, unexpectedly compounding  
426 the fact that worms are more stressed in progradation phase bioconstructions. Arachidonic  
427 acid is a precursor of hormones involved in stress response and levels increase for example  
428 with increasing temperature in *S. alveolata* (Muir et al., 2016). These authors found that  
429 across six sampling stations spanning Scotland to Morocco, the level of 20:4n-6 was lowest in  
430 worms collected in the Bay of Mont-Saint-Michel where environmental conditions were  
431 perceived to be the most favourable (*e.g.* hydrodynamics and sediment supply). Indeed, this is  
432 a central population within the geographic distribution of *S. alveolata* and supports the largest  
433 living biogenic reefs in Europe. Differences in 20:4n-6 observed between the two  
434 bioconstruction phases in our study were however weak (0.25%) compared to existing natural  
435 variability across the range (1-5%, Muir et al., 2016). Membrane 20:4n-6 is therefore a good

436 indicator of stress, as it can detect differences locally as well as across a species distribution  
437 range and is therefore applicable at several scales.

438 Citrate synthase activity (CS) was twice as high in worms sampled in the retrogradation phase  
439 compared to the progradation phase. The CS involved in ATP generation reflects the oxygen  
440 consumption rate of animals and has been used in community ecology to evaluate the  
441 physiological status of rocky intertidal invertebrates (Dahlhoff et al., 2002). CS varies in  
442 response to multiple variables. For example, CS in marine invertebrates increases with food  
443 availability (Dowd et al., 2013), growth rate (Garcia-Esquivel et al., 2002), maintenance costs  
444 and mitochondrial density (Moyes, 2003). Therefore, the elevated levels of CS presented here  
445 require interpretation in conjunction with other markers. In our study, the observed increase in  
446 CS in retrograding bioconstructions coincided with higher levels of stored lipid reserves, as  
447 reflected by the higher neutral:polar lipid ratio. Therefore, it may reflect a feeding-induced  
448 increase in aerobic metabolism as reported in fish larvae (Ferron and Leggett, 1994) and  
449 intertidal invertebrates (Dahlhoff, 2002). Although superoxide dismutase activity (SOD) was  
450 not significantly influenced by overall bioconstruction characteristics, SOD correlated with  
451 CS and was higher in the retrogradation phase. This also points towards worms sampled in  
452 retrograding bioconstructions having a faster metabolism, as SOD processes the ROS  
453 metabolic by-products produced through aerobic respiration (Abele and Puntarulo, 2004).

454 To sum up, high neutral:polar lipids, low 20:4n-6, high CS, high SOD and undepleted  
455 carbohydrates all indicate that worms sampled in retrograding bioconstructions were not  
456 stressed, but rather had either a higher quantity or quality of food source. As all trophic  
457 markers were remarkably similar between the two bioconstruction phases, worms sampled in  
458 the retrogradation phase reef probably had access to food of the same quality but in greater  
459 quantity. Intraspecific competition in a densely-populated progradation-phase bioconstruction

460 is a source of physiological stress due to limited food availability (Connell, 1983).  
461 Alternatively, retrograding bioconstructions harbour more small cracks and crevices filled  
462 with deposited sediment on top of which microphytobenthos can grow and that can be made  
463 available through resuspension processes (Dubois et al., 2007; Lefebvre et al., 2009; Jones et  
464 al., 2018). Microphytobenthos is mostly composed of benthic diatoms, which are of great  
465 dietary value, compared to phytoplankton (Miller et al., 1996).

466 Existing assessments of the health of biogenic habitats depend primarily on visual criteria.  
467 Certain aspects of the health of tropical coral reef polyps have made use of biochemical  
468 markers, by assessing the size of energy stores (as lipid content) as a proxy for physiological  
469 condition (Anthony, 2006) or by using CS and energy-storage lipids to see how scleractinian  
470 coral larvae respond to ocean acidification and warming (Rivest and Hoffmann 2014; Rivest  
471 et al., 2017). However, none of these studies made a link between the coral polyps and their  
472 calcareous skeleton. Attempting to join the physical appearance of a bioconstruction with the  
473 physiological status of the engineering species is surprisingly new.

474 Our study confirms that designating a given *S. alveolata* bioconstruction as retrograding or  
475 prograding leaves room for interpretation, as shown for coral reefs (Abelson et al., 2017).  
476 Health criteria based on the physical appearance of the bioconstruction did not yield any  
477 information on the processes regulating individuals. Yet our results show that worms present  
478 in retrogradation phase bioconstructions are in a better physiological state compared to  
479 progradation phase worms. In a recent study, Jones et al. (2018) demonstrated the ecological  
480 value of retrograding (referred to as “degraded reef”) *S. alveolata* bioconstructions which, due  
481 to their increased micro-habitat availability, act as biodiversity and recruitment promoters and  
482 harbour more diversified food sources. *S. alveolata* colonies, in their role as habitats, may be  
483 of considerable value to certain species of very small animals (Wilson, 1971), with

484 retrograding bioconstructions showing high numbers of associated species (Porras et al.,  
485 1996; Dubois et al., 2002; Jones et al., 2018).

486

487 Although further work is needed to address large-scale variation over time, our results suggest  
488 that *S. alveolata* sampled in retrograding bioconstructions were in fact healthier. The only  
489 signs of ecosystem distress in the retrogradation phase are value judgments about the  
490 bioconstruction appearance. Prograding bioconstructions, with their rounded shapes and crisp  
491 porches, are often considered more aesthetically appealing than silty, pitted retrograding  
492 bioconstructions. Although visual beauty correlates with ecosystem health for tropical coral  
493 reefs (Haas et al., 2015), this does not appear to be the case for other *S. alveolata*  
494 bioconstructions.

495

496 The majority of shorelines where *S. alveolata* are present host a mosaic of bioconstruction  
497 types of varying heights and surface areas. With the exception of 20:1n-11, all of the  
498 examined parameters did not vary between bioconstruction types. Hummock and veneer  
499 sampling points were well interspersed and, due to the Mont-Saint-Michel's bay megatidal  
500 regime, were subjected to a homogeneous water mass. None of the biochemical parameters  
501 varied significantly between the high and low shore. Although the intertidal zone is a stressful  
502 environment (Helmuth et al., 2002; Bertness et al., 2009; Firth and Williams 2009; Firth et al.,  
503 2011), the buffering role that *S. alveolata* bioconstructions play diminishes fluctuations in  
504 temperature and humidity to the point where they are able to host a number of subtidal species  
505 (Dubois et al., 2002; Jones et al., 2018 and unpublished temperature data). It is worth  
506 mentioning that the bathymetric differences between the high and low shore sampling points  
507 were minor (*ca.* 1.5 m) compared to the tidal amplitude in the Mont-Saint-Michel (>14 m).  
508 This could explain why shore level had no effect in our sampling design. Hummocks found



509 lower down the shore reach a greater height relative to sea level. However, this feature is  
510 common for *S. alveolata* bioconstructions which develop around the mid-tide level, with the  
511 bioconstructions located highest on the shore being submerged at least one hour less than the  
512 bioconstructions in the low intertidal zone. In an area experiencing a semidiurnal tide cycle,  
513 this translates as four less hours to filter-feed per lunar day, hence explaining why the largest  
514 individuals are typically found in the bioconstructions lowest down the shore.

515

516 There was a five-fold difference in individual wet weight across sampled individuals, with  
517 specimens ranging from ~70 to ~350 mg. We found that energetic reserves, CS, 22:6n-3 in  
518 phospholipids and four out of six trophic markers were correlated with size. It is therefore  
519 vital to take *S. alveolata* individual size into consideration when analyzing biochemical  
520 variables, something that is not systematically done in marine invertebrate biochemical  
521 studies. Carbohydrate and protein concentrations diminished with individual mass whereas  
522 neutral lipids increased, reflecting a size-specific biochemical composition. All of the sampled  
523 individuals were mature and collected at the adult stage. Therefore, size may be confounded  
524 with age, and differences in biochemical composition could reflect either. Both CS and 22:6n-  
525 3 decreased with increasing individual mass. Body mass and basal metabolic rates are  
526 allometrically related (Hochachka and Somero , 2002). Our results suggest that differences in  
527 respiration rate in *S. alveolata* relate to cell membrane fatty acid composition. This is  
528 consistent with Hulbert's theory of membranes as metabolic pacemakers (Hulbert et al.,  
529 2005).

530

531 We found that the neutral:polar lipid ratio and five out of six neutral lipid fatty acid trophic  
532 markers were higher in female worms, whereas 22:6n-3, the carnivory trophic marker and CS  
533 were all significantly higher in male worms. Docosaheptaenoic acid (DHA – 22:6n-3) is

534 abundant in spermatozoa (Masuda, 2003), and hence is the only polar lipid fatty acid  
535 significantly higher in males. Invertebrate eggs typically contain few carbohydrates and are  
536 mainly composed of energy dense proteins and lipids, hence explaining higher neutral lipid  
537 contents in females (Pernet and Jaeckle, 2004). Female worms stored four times more neutral  
538 lipids than males. The neutral lipid fatty acid composition is transferred more conservatively  
539 than the polar lipid fraction and therefore mirrors more closely that of the diet. Females  
540 containing high neutral lipid levels are more susceptible to dietary change than males which  
541 contain mostly polar lipids. This renders neutral lipid-rich female *S. alveolata* more suitable  
542 than males for representing trophic-related changes in the environment, especially when  
543 investigating diets or changes in food source composition. In order to use biochemical  
544 indicators for studying trophic interactions, it is therefore important to be able to distinguish  
545 the two sexes and to sample and analyse female *S. alveolata*.

546 Our study examined a one-time sampling event at a single study location. Increased spatio-  
547 temporal sampling may further clarify differences between the long-term physical changes of  
548 the bioconstruction and the short-term physiological state of the worm. In the progradation  
549 phase, *S. alveolata* individuals displayed biochemical stress markers. However, this may be  
550 considered as temporary stress due to, for example, momentarily lacking sufficient food. A  
551 bioconstruction can move rapidly between progradation and retrogradation phases and is  
552 therefore an inherent or “natural” fluctuation. An alternative scenario is that the worm  
553 population is physiologically stressed beyond recovery. When resilience is exceeded, the  
554 future of the bioconstruction is entirely dependent on primary or secondary settlement, thus  
555 reflecting some kind of fundamental change in underlying dynamics (Johnson, 2009).  
556 Although retrograding bioconstructions support worms in a better physiological condition, the  
557 high diversity this phase supports may have a negative effect both on adult worms through

558 interspecific competition, and on *S. alveolata* larval recruitment, as epiflora can lower  
559 successful recruit density due to the mechanical action of algal fronds sweeping the reef  
560 surface (Dubois et al., 2006). Bioconstructions will no doubt naturally undergo a cycle of  
561 progradation and retrogradation. However, when resilience is exceeded the balance between  
562 these two phases is upset and may cause the system to “flip” to an alternative state (Fung et  
563 al., 2011). An ecosystem’s health can be defined in terms of system vigour, organisation and  
564 resilience (Costanza, 1992). Whilst existing ecological studies attest to retrograding *S.*  
565 *alveolata* bioconstruction vigour and organisation (Dubois et al., 2002; Jones et al., 2018),  
566 further work is needed to quantify their resilience.

567

568 The European Habitats Directive, and the overarching Marine Strategy Framework Directive  
569 (MSFD, 2008/56/EC) give statutory significance to the definition of a “reef”. Crucially, the  
570 distinction between what is considered as “reef” and what is not, is imprecise. Which *S.*  
571 *alveolata* bioconstruction type, and which progradation/retrogradation phase criteria are of  
572 conservation value, are yet to be defined. This has far-reaching implications in terms of  
573 environmental management and conservation. The offset between the physical state of the  
574 bioconstruction and the physiological state of the worm makes it vital to analyse the two  
575 together, and to understand the natural history and physiology of one’s study organisms when  
576 using biochemical indicators for ecological studies (Dahlhoff, 2004). Seasonal, broad-scale  
577 studies are therefore warranted to further our understanding of the link between the engineer  
578 species and the engineered habitat it creates.

## 579 **5. Conclusion**

580 The metabolic enzymes citrate synthase and superoxide dismutase, when analysed in  
581 conjunction with the polar lipid fatty acid 20:4n-6, serve as stress markers for the

582 physiological state of *S. alveolata*. Once seasonal and inter-site variation have been addressed,  
583 these three biochemical indicators could be looked at in priority, in concurrence with *S.*  
584 *alveolata* bioconstruction physical criteria, as part of a European-wide monitoring protocol.  
585 Member states will be updating their MSFD monitoring programme and measures in the  
586 coming years and are being urged by the European Commission for a coherent and  
587 coordinated approach within and between marine regions. Although exploratory biochemical  
588 analyses time and money costs are high, they greatly diminish with subsequent routine  
589 screening of a few key indicators. Furthermore, few worm specimens are needed and their  
590 collection is substantially less destructive than the sediment core sampling typically used for  
591 obtaining biodiversity metrics. Whereas physical bioconstruction parameters are site-specific,  
592 biochemical indicators are applicable across a species range and therefore serve as large-scale,  
593 quantitative metrics, provided that sex and size are controlled for.

#### 594 **Conflict of interest**

595 The authors declare that they have no conflict of interest.

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#### 603 **References**

- 604 Aebi, H., 1984. [13] Catalase in vitro, in: Methods in Enzymology. Elsevier, pp. 121–126.  
605 [https://doi.org/10.1016/S0076-6879\(84\)05016-3](https://doi.org/10.1016/S0076-6879(84)05016-3)
- 606 Abele, D., Puntarulo, S., 2004. Formation of reactive species and induction of antioxidant  
607 defence systems in polar and temperate marine invertebrates and fish. Comparative  
608 Biochemistry and Physiology Part A: Molecular & Integrative Physiology 138, 405–  
609 415. <https://doi.org/10.1016/j.cbpb.2004.05.013>
- 610 Abelson, A., Nelson, P.A., Edgar, G.J., Shashar, N., Reed, D.C., Belmaker, J., Krause, G.,  
611 Beck, M.W., Brokovich, E., France, R. and Gaines, S.D., 2016. Expanding marine  
612 protected areas to include degraded coral reefs. Conservation Biology, 30: 1182–1191.  
613 doi:10.1111/cobi.12722
- 614 Anthony, K., 2006. Enhanced energy status of corals on coastal, high-turbidity reefs. Marine  
615 Ecology Progress Series 319, 111–116. doi:10.3354/meps319111
- 616 Bartol, I.K., Mann, R., Luckenbach, M., 1999. Growth and mortality of oysters (*Crassostrea*  
617 *virginica*) on constructed intertidal reefs: effects of tidal height and substrate level.  
618 Journal of Experimental Marine Biology and Ecology 237, 157–184.  
619 [https://doi.org/10.1016/S0022-0981\(98\)00175-0](https://doi.org/10.1016/S0022-0981(98)00175-0)
- 620 Berthelin, C., Kellner, K., Mathieu, M.,  
621 2000. Storage metabolism in the Pacific oyster (*Crassostrea gigas*) in relation to  
622 summer mortalities and reproductive cycle (West Coast of France). Comparative  
623 Biochemistry and Physiology Part B: Biochemistry and Molecular Biology 125, 359–  
369. [https://doi.org/10.1016/S0305-0491\(99\)00187-X](https://doi.org/10.1016/S0305-0491(99)00187-X)
- 624 Bertness, M.D., Leonard, G.H., Levine, J.M., Schmidt, P.R., Ingraham, A.O., 1999. Testing  
625 the relative contribution of positive and negative interactions in rocky intertidal  
626 communities. Ecology 80, 2711–2726. [https://doi.org/10.1890/0012-9658\(1999\)080\[2711:TTRCOP\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[2711:TTRCOP]2.0.CO;2)
- 628 Bligh, E.G., Dyer, W.J., 1959. A Rapid Method of Total Lipid Extraction and Purification.  
629 Canadian Journal of Biochemistry and Physiology 37, 911–917.  
630 <https://doi.org/10.1139/o59-099>
- 631 Box, G.E.P., Cox, D.R., 1964. An Analysis of Transformations. Journal of the Royal  
632 Statistical Society. Series B (Methodological) 26, 211–252.
- 633 Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., West, G.B., 2004. Toward a Metabolic  
634 Theory of Ecology. Ecology 85, 1771–1789. <https://doi.org/10.1890/03-9000>
- 635 Childress, J.J., Somero, G.N., 1979. Depth-related enzymic activities in muscle, brain and  
636 heart of deep-living pelagic marine teleosts. Marine Biology 52, 273–283.  
637 <https://doi.org/10.1007/BF00398141>
- 638 Connell, J.H., 1983. On the Prevalence and Relative Importance of Interspecific Competition:  
639 Evidence from Field Experiments. The American Naturalist 122, 661–696.  
640 <https://doi.org/10.1086/284165>
- 641 Costanza, R., 1992. Towards an operational definition of ecosystem health, in: Ecosystem  
642 Health: New Goals for Environmental Management. Island Press, pp. 239–256.
- 643 Culloty, S.C., Favier, E., Ní Riada, M., Ramsay, N.F., O’Riordan, R.M., 2010. Reproduction  
644 of the biogenic reef-forming honeycomb worm *Sabellaria alveolata* in Ireland. Journal  
645 of the Marine Biological Association of the United Kingdom 90, 503.  
646 <https://doi.org/10.1017/S0025315409990932>

- 647 Cunningham, P.N., 1984. The geographical distribution of *Sabellaria alveolata* (L.) in  
648 England, Wales and Scotland, with investigations into the community structure of, and  
649 the effects of trampling on *Sabellaria alveolata* colonies. (N.C.C. Contract No.  
650 HF3/11/22.).
- 651 Dalsgaard J., St. John, M., Kattner, G., Muller-Navarra, D., Hagen, W., 2003. Fatty acid  
652 trophic markers in the pelagic marine environment. *Advances in Marine Biology*  
653 46:225-340. doi: 10.1016/S0065-2881(03)46005-7
- 654 Dahlhoff, E.P., Stillman, J.H., Menge, B.A., 2002. Physiological community ecology:  
655 variation in metabolic activity of ecologically important rocky intertidal invertebrates  
656 along environmental gradients. *Integrative and comparative biology* 42, 862–871.
- 657 Dahlhoff, E.P., 2004. Biochemical Indicators of Stress and Metabolism: Applications for  
658 Marine Ecological Studies. *Annual Review of Physiology* 66, 183–207.  
659 <https://doi.org/10.1146/annurev.physiol.66.032102.114509>
- 660 Delaporte, M., 2003. Effect of a mono-specific algal diet on immune functions in two bivalve  
661 species - *Crassostrea gigas* and *Ruditapes philippinarum*. *Journal of Experimental*  
662 *Biology* 206, 3053–3064. <https://doi.org/10.1242/jeb.00518>
- 663 Desroy, N., Dubois, S.F., Fournier, J., Ricquiers, L., Le Mao, P., Guerin, L., Gerla, D.,  
664 Rougerie, M., Legendre, A., 2011. The conservation status of *Sabellaria alveolata* (L.)  
665 (Polychaeta: Sabellariidae) reefs in the Bay of Mont-Saint-Michel. *Aquatic*  
666 *Conservation: Marine and Freshwater Ecosystems* 21, 462–471. doi:10.1002/aqc.1206
- 667 Dowd, W.W., Felton, C.A., Heymann, H.M., Kost, L.E., Somero, G.N., 2013. Food  
668 availability, more than body temperature, drives correlated shifts in ATP-generating and  
669 antioxidant enzyme capacities in a population of intertidal mussels (*Mytilus*  
670 *californianus*). *Journal of Experimental Marine Biology and Ecology* 449, 171-185.
- 671 Dubois, S., Retière, C., Olivier, F., 2002. Biodiversity associated with *Sabellaria alveolata*  
672 (Polychaeta: Sabellariidae) reefs: effects of human disturbances. *Journal of the Marine*  
673 *Biological Association of the UK* 82, 817–826. doi:10.1017/S0025315402006185
- 674 Dubois, S., Commito, J.A., Olivier, F., Retière, C., 2006. Effects of epibionts on *Sabellaria*  
675 *alveolata* (L.) biogenic reefs and their associated fauna in the Bay of Mont Saint-  
676 Michel. *Estuarine, Coastal and Shelf Science* 68, 635–646.  
677 <https://doi.org/10.1016/j.ecss.2006.03.010>
- 678 Dubois, S., Orvain, F., Marin-Léal, J., Ropert, M., Lefebvre, S., 2007. Small-scale spatial  
679 variability of food partitioning between cultivated oysters and associated suspension-  
680 feeding species, as revealed by stable isotopes. *Marine Ecology Progress Series* 336,  
681 151–160. <https://doi.org/10.3354/meps336151>
- 682 Dubois, S.F., Colombo, F., 2014. How picky can you be? Temporal variations in trophic  
683 niches of co-occurring suspension-feeding species. *Food Webs* 1, 1–9.  
684 <https://doi.org/10.1016/j.fooweb.2014.07.001>
- 685 DuBois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.A., Smith, F., 1956. Colorimetric Method  
686 for Determination of Sugars and Related Substances. *Analytical Chemistry* 28, 350–  
687 356. <https://doi.org/10.1021/ac60111a017>

- 688 Ellis, R.P., Parry, H., Spicer, J.I., Hutchinson, T.H., Pipe, R.K., Widdicombe, S., 2011.  
689 Immunological function in marine invertebrates: Responses to environmental  
690 perturbation. *Fish & Shellfish Immunology* 30, 1209–1222.  
691 <https://doi.org/10.1016/j.fsi.2011.03.017>
- 692 Ferron, A., Leggett, W.C., 1994. An Appraisal of Condition Measures for Marine Fish  
693 Larvae, in: *Advances in Marine Biology*. Elsevier, pp. 217–303.  
694 [https://doi.org/10.1016/S0065-2881\(08\)60064-4](https://doi.org/10.1016/S0065-2881(08)60064-4)
- 695 Firth, L.B., Williams, G.A., 2009. The influence of multiple environmental stressors on the  
696 limpet *Cellana toreuma* during the summer monsoon season in Hong Kong. *Journal of*  
697 *Experimental Marine Biology and Ecology* 375, 70–75.  
698 <https://doi.org/10.1016/j.jembe.2009.05.011>
- 699 Firth, L.B., Knights, A.M., Bell, S.S., 2011. Air temperature and winter mortality:  
700 Implications for the persistence of the invasive mussel, *Perna viridis* in the intertidal  
701 zone of the south-eastern United States. *Journal of Experimental Marine Biology and*  
702 *Ecology* 400, 250–256. <https://doi.org/10.1016/j.jembe.2011.02.007>
- 703 Firth, L.B., Mieszkowska, N., Grant, L.M., Bush, L.E., Davies, A.J., Frost, M.T., Moschella,  
704 P.S., Burrows, M.T., Cunningham, P.N., Dye, S.R., Hawkins, S.J., 2015. Historical  
705 comparisons reveal multiple drivers of decadal change of an ecosystem engineer at the  
706 range edge. *Ecology and Evolution* 5, 3210–3222.  
707 <https://doi.org/10.1002/ece3.1556>
- 708 Fraser, A.J., 1989. Triacylglycerol Content as a  
709 Condition Index for Fish, Bivalve, and Crustacean Larvae. *Canadian Journal of*  
*Fisheries and Aquatic Sciences* 46, 1868–1873. <https://doi.org/10.1139/f89-235>
- 710 Fuhrmann, M., Delisle, L., Petton, B., Corporeau, C., Pernet, F., 2018. Metabolism of the  
711 Pacific oyster, *Crassostrea gigas*, is influenced by salinity and modulates survival to  
712 the Ostreid herpesvirus OsHV-1. *Biology Open* 7, bio028134.  
713 <https://doi.org/10.1242/bio.028134>
- 714 Fung, T., Seymour, R.M., Johnson, C.R., 2011. Alternative stable states and phase shifts in  
715 coral reefs under anthropogenic stress. *Ecology* 92, 967–982.  
716 <https://doi.org/10.1890/10-0378.1>
- 717 Gabbott, P.A., 1975. Storage cycles in marine bivalve molluscs: a hypothesis concerning the  
718 relationship between glycogen metabolism and gametogenesis. Presented at the Ninth  
719 European Marine Biology Symposium, Aberdeen University Press, Oban, pp. 191–211.
- 720 Gallager, S.M., Mann, R., Sasaki, G.C., 1986. Lipid as an index of growth and viability in  
721 three species of bivalve larvae. *Aquaculture* 56, 81–103. [https://doi.org/10.1016/0044-8486\(86\)90020-7](https://doi.org/10.1016/0044-8486(86)90020-7)
- 722
- 723 Garcia-Esquivel, Z., Bricelj, V.M., Felbeck, H., 2002. Metabolic depression and whole-body  
724 response to enforced starvation by *Crassostrea gigas* postlarvae. *Comparative*  
725 *Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 133, 63–77.  
726
- 727 Goldberg, W.M., 2013. *The biology of reefs and reef organisms*. University of Chicago Press,  
728 Chicago.

- 729 Gruet, Y., 1982. Recherches sur l'écologie des "récifs" d'hermelles édifiés par l'Annélide  
730 Polychète *Sabellaria alveolata* (Linné). (Thèse Doctorat d'Etat). Nantes.
- 731 Gruet, Y., 1986. Spatio-temporal Changes of Sabellarian Reefs Built by the Sedentary  
732 Polychaete *Sabellaria alveolata* (Linné). *Marine Ecology* 7, 303–319.  
733 doi:10.1111/j.1439-0485.1986.tb00166.x
- 734 Haas, A.F., Guibert, M., Foerschner, A., Co, T., Calhoun, S., George, E., Hatay, M., Dinsdale,  
735 E., Sandin, S.A., Smith, J.E., Vermeij, M.J.A., Felts, B., Dustan, P., Salamon, P.,  
736 Rohwer, F., 2015. Can we measure beauty? Computational evaluation of coral reef  
737 aesthetics. *PeerJ* 3, e1390. <https://doi.org/10.7717/peerj.1390>
- 738 Hattam, C., Atkins, J.P., Beaumont, N., Börger, T., Böhnke-Henrichs, A., Burdon, D., Groot,  
739 R. de, Hoefnagel, E., Nunes, P.A.L.D., Piwowarczyk, J., Sastre, S., Austen, M.C., 2015.  
740 Marine ecosystem services: Linking indicators to their classification. *Ecological*  
741 *Indicators* 49, 61–75. <https://doi.org/10.1016/j.ecolind.2014.09.026>
- 742 Hazel, J.R., 1995. Thermal Adaptation in Biological Membranes: Is Homeoviscous  
743 Adaptation the Explanation? *Annual Review of Physiology* 57, 19–42.  
744 <https://doi.org/10.1146/annurev.ph.57.030195.000315>
- 745 Hazel, J.R., Williams, E.E., 1990. The role of alterations in membrane lipid composition in  
746 enabling physiological adaptation of organisms to their physical environment. *Progress*  
747 *in Lipid Research* 29, 167–227. [https://doi.org/10.1016/0163-7827\(90\)90002-3](https://doi.org/10.1016/0163-7827(90)90002-3)
- 748 Helmuth, B., Harley, C.D.G., Halpin, P.M., O'Donnell, M., Hofmann, G.E., Blanchette, C.A.,  
749 2002. Climate Change and Latitudinal Patterns of Intertidal Thermal Stress. *Science*  
750 298, 1015–1017. <https://doi.org/10.1126/science.1076814>
- 751 Hendrick, V.J., Foster-Smith, R.L., 2006. *Sabellaria spinulosa* reef: a scoring system for  
752 evaluating 'reefiness' in the context of the Habitats Directive. *Journal of the Marine*  
753 *Biological Association of the UK* 86, 665. doi:10.1017/S0025315406013555
- 754 Hentschel, B.T., 1998. Spectrofluorometric quantification of neutral and polar lipids suggests  
755 a food-related recruitment bottleneck for juveniles of a deposit-feeding polychaete  
756 population. *Limnology and Oceanography* 43, 543–549.  
757 <https://doi.org/10.4319/lo.1998.43.3.0543>
- 758 Hochachka, P.W., Somero, G.N., 2002. Biochemical adaptation: mechanism and process in  
759 physiological evolution. Oxford University Press, New York.
- 760 Holt, T.J., Rees, E.I., Hawkins, S.J., Seed, R., 1998. Biogenic Reefs. An overview of dynamic  
761 and sensitivity characteristics for conservation management of marine SACs. (No.  
762 volume IX). Scottish Association for Marine Science (UK Marine SACs Project).
- 763 Hulbert, A.J., Turner, N., Storlien, L.H., Else, P.L., 2005. Dietary fats and membrane  
764 function: implications for metabolism and disease. *Biological Reviews* 80, 155–169.  
765 <https://doi.org/10.1017/S1464793104006578>
- 766 Johnson, C.R., 2009. Natural Length Scales of Ecological Systems: Applications at  
767 Community and Ecosystem Levels. *Ecology and Society* 14. doi:10.5751/ES-02749-  
768 140107
- 769 Jones, A.G., Dubois, S.F., Desroy, N., Fournier, J., 2018. Interplay between abiotic factors  
770 and species assemblages mediated by the ecosystem engineer *Sabellaria alveolata*  
771 (Annelida: Polychaeta). *Estuarine, Coastal and Shelf Science* 200, 1–18.  
772 doi:10.1016/j.ecss.2017.10.001



- 773 Le Foll, C., Corporeau, C., Le Guen, V., Gouygou, J.-P., Berge, J.-P., Delarue, J., 2006.  
 774 Long-chain n-3 polyunsaturated fatty acids dissociate phosphorylation of Akt from  
 775 phosphatidylinositol 3'-kinase activity in rats. *AJP: Endocrinology and Metabolism*  
 776 292, E1223–E1230. <https://doi.org/10.1152/ajpendo.00446.2006>
- 777 Lefebvre, S., Marín Leal, J.C., Dubois, S., Orvain, F., Blin, J.-L., Bataillé, M.-P., Ourry, A.,  
 778 Galois, R., 2009. Seasonal dynamics of trophic relationships among co-occurring  
 779 suspension-feeders in two shellfish culture dominated ecosystems. *Estuarine, Coastal*  
 780 *and Shelf Science* 82, 415–425. <https://doi.org/10.1016/j.ecss.2009.02.002>
- 781 Lesser, M.P., 2006. Oxidative Stress in Marine Environments: Biochemistry and  
 782 Physiological Ecology. *Annual Review of Physiology* 68, 253–278.  
 783 <https://doi.org/10.1146/annurev.physiol.68.040104.110001>
- 784 Levoy, F., Anthony, E.J., Monfort, O., Larsonneur, C., 2000. The morphodynamics of  
 785 megatidal beaches in Normandy, France. *Marine Geology* 171, 39–59.  
 786 [https://doi.org/10.1016/S0025-3227\(00\)00110-9](https://doi.org/10.1016/S0025-3227(00)00110-9)
- 787 Lochmiller, R.L., Deerenberg, C., 2000. Trade-offs in evolutionary immunology: just what is  
 788 the cost of immunity? *Oikos* 88, 87–98. <https://doi.org/10.1034/j.1600-0706.2000.880110.x>
- 790 Lourenço, S., Roura, Á., Fernández-Reiriz, M.-J., Narciso, L., González, Á.F., 2017. Feeding  
 791 Relationship between *Octopus vulgaris* (Cuvier, 1797) Early Life-Cycle Stages and  
 792 Their Prey in the Western Iberian Upwelling System: Correlation of Reciprocal Lipid  
 793 and Fatty Acid Contents. *Frontiers in Physiology* 8.  
 794 <https://doi.org/10.3389/fphys.2017.00467>
- 795 Lowry, O. H., Rosebrough, N. J., Farr, A. L. and Randall, R. J., 1951. Protein measurement  
 796 with the Folin phenol reagent. *The Journal of Biological Chemistry* 193, 265-75.
- 797 Lucas, A., Beninger, P.G., 1985. The use of physiological condition indices in marine bivalve  
 798 aquaculture. *Aquaculture* 44, 187–200. [https://doi.org/10.1016/0044-8486\(85\)90243-1](https://doi.org/10.1016/0044-8486(85)90243-1)
- 799 Marty, Y., Delaunay, F., Moal, J., Samain, J.-F., 1992. Changes in the fatty acid composition  
 800 of *Pecten maximus* (L.) during larval development. *Journal of Experimental Marine*  
 801 *Biology and Ecology* 163, 221–234. [https://doi.org/10.1016/0022-0981\(92\)90051-B](https://doi.org/10.1016/0022-0981(92)90051-B)
- 802 Masuda, R., 2003. The critical role of docosahexaenoic acid in marine and terrestrial  
 803 ecosystems: from bacteria to human behavior, in: *The Big Fish Bang. Proceedings of*  
 804 *the 26th Annual Larval Fish Conference*. Howard I. Browman & Anne Berit Skiftesvik,  
 805 Os, Norway, pp. 249–256.
- 806 Metcalfe, L.D., Schmitz, A.A., 1961. The Rapid Preparation of Fatty Acid Esters for Gas  
 807 Chromatographic Analysis. *Analytical Chemistry* 33, 363–364.  
 808 <https://doi.org/10.1021/ac60171a016>
- 809 Miller, D.C., Geider, R.J. and MacIntyre, H.L., 1996. Microphytobenthos: the ecological role  
 810 of the “secret garden” of unvegetated, shallow-water marine habitats. II. Role in  
 811 sediment stability and shallow-water food webs. *Estuaries*, 19(2), 202-212.
- 812 Morrison, W. R. and Smith, L. M., 1964. Preparation of fatty acid methyl esters and  
 813 dimethylacetals from lipids with boron fluoride-methanol. *Journal of Lipid Research* 5,  
 814 600-8.
- 815 Moyes, C.D., 2003. Controlling muscle mitochondrial content. *Journal of Experimental*  
 816 *Biology* 206, 4385–4391. <https://doi.org/10.1242/jeb.00699>

- 817 Muir, A.P., Nunes, F.L.D., Dubois, S.F., Pernet, F., 2016. Lipid remodelling in the reef-  
818 building honeycomb worm, *Sabellaria alveolata*, reflects acclimation and local  
819 adaptation to temperature. *Scientific Reports* 6, 35669. doi:10.1038/srep35669
- 820 Osada, M., Nishikawa, M., Nomura, T., 1989. Involvement of prostaglandins in the spawning  
821 of the scallop, *Patinopecten yessoensis*. *Comparative Biochemistry and Physiology. C:*  
822 *Comparative Pharmacology* 94, 595–601.
- 823  
824 Pawlik, J.R., 1986. Chemical induction of larval settlement and metamorphosis in the reef-  
825 building tube worm *Phragmatopoma californica* (Sabellariidae: Polychaeta). *Marine*  
826 *Biology* 91, 59–68. <https://doi.org/10.1007/BF00397571>
- 827 Pernet, F., Lagarde, F., Jeannée, N., Daigle, G., Barret, J., Le Gall, P., Quere, C., D'orbcastel,  
828 E.R., 2014. Spatial and Temporal Dynamics of Mass Mortalities in Oysters Is  
829 Influenced by Energetic Reserves and Food Quality. *PLoS ONE* 9, e88469.  
830 <https://doi.org/10.1371/journal.pone.0088469>
- 831 Pernet, F., Tremblay, R., Comeau, L., Guderley, H., 2007. Temperature adaptation in two  
832 bivalve species from different thermal habitats: energetics and remodelling of  
833 membrane lipids. *Journal of Experimental Biology* 210, 2999–3014.  
834 <https://doi.org/10.1242/jeb.006007>
- 835 Pernet, B., Jaeckle, W.B., 2004. Size and Organic Content of Eggs of Marine Annelids, and  
836 the Underestimation of Egg Energy Content by Dichromate Oxidation. *The Biological*  
837 *Bulletin* 207, 67–71. <https://doi.org/10.2307/1543629>
- 838 Plicanti, A., Domínguez, R., Dubois, S.F., Bertocci, I., 2016. Human impacts on biogenic  
839 habitats: Effects of experimental trampling on *Sabellaria alveolata* (Linnaeus, 1767)  
840 reefs. *Journal of Experimental Marine Biology and Ecology* 478, 34–44.  
841 <https://doi.org/10.1016/j.jembe.2016.02.001>
- 842 Porras, R., Bataller, J.V., Murgui, E., Torregrosa, M.T., 1996. Trophic Structure and  
843 Community Composition of Polychaetes Inhabiting Some *Sabellaria alveolata* (L.)  
844 Reefs Along the Valencia Gulf Coast, Western Mediterranean. *Marine Ecology* 17,  
845 583–602. <https://doi.org/10.1111/j.1439-0485.1996.tb00419.x>
- 846 Rivest, E.B., Chen, C.-S., Fan, T.-Y., Li, H.-H., Hofmann, G.E., 2017. Lipid consumption in  
847 coral larvae differs among sites: a consideration of environmental history in a global  
848 ocean change scenario. *Proceedings of the Royal Society B: Biological Sciences* 284,  
849 20162825. <https://doi.org/10.1098/rspb.2016.2825>
- 850 Rivest, E.B., Hofmann, G.E., 2014. Responses of the Metabolism of the Larvae of  
851 *Pocillopora damicornis* to Ocean Acidification and Warming. *PLoS ONE* 9, e96172.  
852 <https://doi.org/10.1371/journal.pone.0096172>
- 853 Scheer, B.T., 1969. Carbohydrates and carbohydrate metabolism: Annelida, Sipuncula,  
854 Echiura. *Chemical zoology*, 4.
- 855 Schimmenti, E., Musco, L., Lo Brutto S., Mikac, B., Nygren, A., Badalamenti, F., 2015 « A  
856 Mediterranean Record of *Eulalia Ornata* (Annelida: Phyllodocidae) Corroborating Its  
857 Fidelity Link with the *Sabellaria Alveolata*-Reef Habitat ». *Mediterranean Marine*  
858 *Science* 17(2): 359-70.
- 859

- 860 Soudant, P., Van Ryckeghem, K., Marty, Y., Moal, J., Samain, J.F., Sorgeloos, P., 1999.  
861 Comparison of the lipid class and fatty acid composition between a reproductive cycle  
862 in nature and a standard hatchery conditioning of the Pacific Oyster *Crassostrea gigas*.  
863 Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular  
864 Biology 123, 209–222. [https://doi.org/10.1016/S0305-0491\(99\)00063-2](https://doi.org/10.1016/S0305-0491(99)00063-2)
- 865 Tessier, B., 1993. Upper intertidal rhythmites in the Mont-Saint-Michel Bay (NW France):  
866 perspectives for paleoreconstruction. Marine Geology 110, 355–367.
- 867 Tremblay, R., Olivier, F., Bourget, E., Rittschof, D., 2007. Physiological condition of *Balanus*  
868 *amphitrite* cyprid larvae determines habitat selection success. Marine Ecology Progress  
869 Series 340, 1–8.
- 870 Wilson, D. 1968. The settlement behaviour of the larvae of *Sabellaria alveolata* (L.). Journal  
871 of the Marine Biological Association of the United Kingdom, 50, 1-45.
- 872 Wilson, D.P., 1971. *Sabellaria* Colonies At Duckpool, North Cornwall, 1961–1970. Journal  
873 of the Marine Biological Association of the United Kingdom 51, 509.  
874 <https://doi.org/10.1017/S002531540001496X>
- 875 Winder, M., Carstensen, J., Galloway, A.W.E., Jakobsen, H.H., Cloern, J.E., 2017. The land-  
876 sea interface: A source of high-quality phytoplankton to support secondary production:  
877 Nutritious phytoplankton support coastal systems. Limnology and Oceanography 62,  
878 S258–S271. <https://doi.org/10.1002/lno.10650>

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880

## 881 **Figure legends**

882 **Figure 1** Conceptual diagram of a) the different bioconstruction Types of *S. alveolata*  
883 (adapted from Gruet, 1986). Progradation and Retrogradation, as defined in b), are  
884 represented by full versus hatched arrows respectively. Note that a bioconstruction can cycle  
885 between the two Phases – as represented by the circular arrows – within the same  
886 bioconstruction Type. Images © Ifremer.

887

888 **Figure 2** Map of the study site with the twelve sampling points. V=Veneer, HR=  
889 Retrograding Hummock, HPHs=Prograding Hummock High Shore, HPLs=Prograding  
890 Hummock Low Shore.

891

892 **Figure 3** Organic macromolecules in the honeycomb worm *Sabellaria alveolata* as a function  
893 of bioconstruction type, bioconstruction phase and shore level (a-c, n=59), worm mass (d-f,  
894 n=59) and sex (g-i n=8 (5 female, 3 male)). All y axis units are  $\text{mg}\cdot\text{g}^{-1}$  tissue. V=Veneer,  
895 H=Hummock, HR=Retrograding Hummock, HP=Prograding Hummock, HPHs=Prograding  
896 Hummock High shore, HPLs=Prograding Hummock Low shore. Carbohydrate statistical test  
897 results are log-transformed. The letters “a” and “b” represent a significant difference in the  
898 contrast test ( $p=0.002$ ). \* =  $p\leq 0.05$ .

899

900 **Figure 4** Polar lipids in the honeycomb worm *Sabellaria alveolata* as a function of  
901 bioconstruction type, bioconstruction phase and shore level (a-d, n=59), worm mass (e-h,  
902 n=59) and sex (i-l, n=8 (5 female, 3 male)). All y axis units are a percentage of total  
903 phospholipids. Note that the y axis scale varies between fatty acids. V=Veneer, H=Hummock,  
904 HR=Retrograding Hummock, HP=Prograding Hummock, HPHs=Prograding Hummock High  
905 shore, HPLs=Prograding Hummock Low shore. 22:6n-3 statistical test results are log-  
906 transformed. The letters “a” and “b” represent a significant difference in the bioconstruction  
907 type contrast test ( $p=0.009$ ), and the letters “c” and “d” in the bioconstruction type contrast  
908 test ( $p=0.024$ ). \* =  $p\leq 0.05$ .

909

910 **Figure 5** Neutral lipids in the honeycomb worm *Sabellaria alveolata* as a function of  
911 bioconstruction type, bioconstruction phase and shore level (a-f, n=59), worm mass (g-k,  
912 n=59) and sex (m-r, n=8 (5 female, 3 male)). All y axis units are a percentage of total neutral  
913 lipids. Note that the y axis scale varies between fatty acids. Diatoms=16:1n-7/16:0;  
914 Dinoflagellates=22:6n-3/20:5n-3; Carnivory=18:1n-9/18:1n-7; Bacterial = 15:0 + 17:0 +

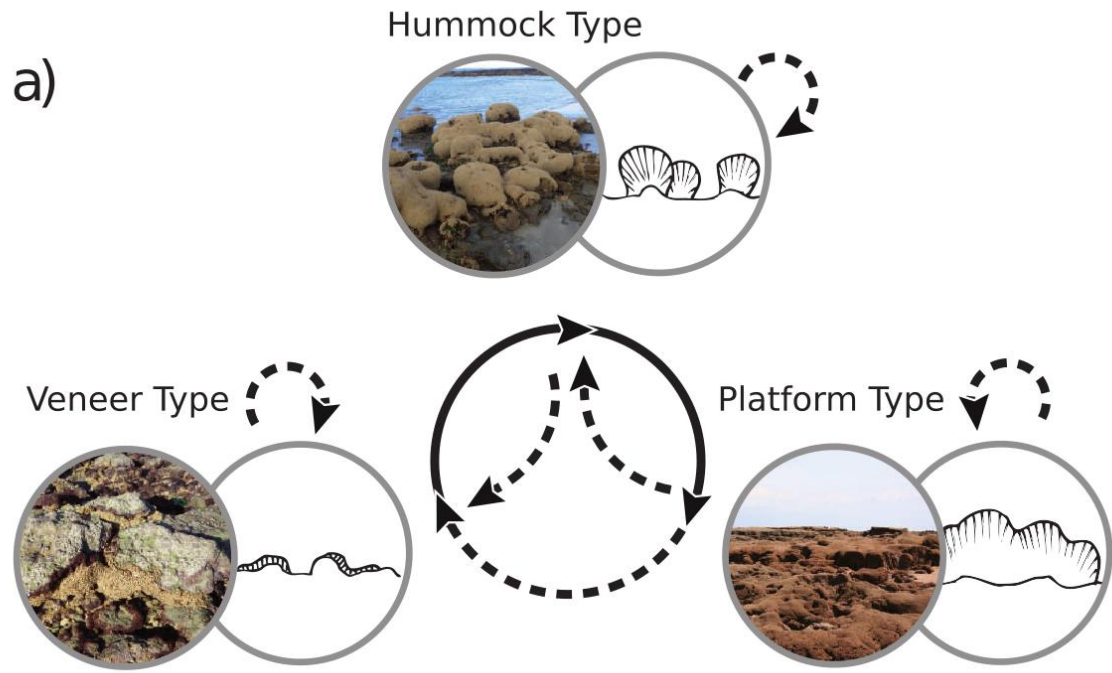
915 branched fatty acids; Terrestrial= 18:2n-6 + 18:3n-3; Freshness= PUFA/SFA. V=Veneer,  
916 H=Hummock, HR=Retrograding Hummock, HP=Prograding Hummock, HPHs=Prograding  
917 Hummock High shore, HPLs=Prograding Hummock Low shore. \* =  $p \leq 0.05$

918 **Figure 6** Enzyme levels in the honeycomb worm *Sabellaria alveolata* as a function of  
919 bioconstruction type, bioconstruction phase and shore level (a-c, n=59), worm mass (d-f,  
920 n=59) and sex (g-I, n=8 (5 female, 3 male)). CS y axis units are micro Units  $\text{mU} \cdot \text{mg}^{-1}$  of  
921 protein, whereas CAT and SOD units are  $\text{U} \cdot \text{mg}^{-1}$  of protein. CS= Citrate synthase,  
922 CAT=Catalase, SOD=Superoxide dismutase. V=Veneer, H=Hummock, HR=Retrograding  
923 Hummock, HP=Prograding Hummock, HPHs=Prograding Hummock High shore,  
924 HPLs=Prograding Hummock Low shore. All statistical test results are log-transformed. The  
925 letters “a” and “b” represent a significant difference in the contrast test ( $p=0.013$ ). \* =  $p \leq 0.05$ .

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Figure 1



b)

#### Progradation Phase

- Dominated by occupied tubes identified by porches
- Limited/No epibionts
- Uniform aspect
- Presence of small tube openings (aperture <2.5 mm) indicating recruitment
- Surface of reef of similar colour to surrounding sediment



#### Retrogradation Phase

- Mosaic of occupied and unoccupied tubes (identified by lack of porches)
- Often featuring epibionts/biofilms
- Signs of reef erosion
- No visible small tube openings (aperture <2.5 mm)
- Surface of reef highly fragmented and dark brown to grey in colouration

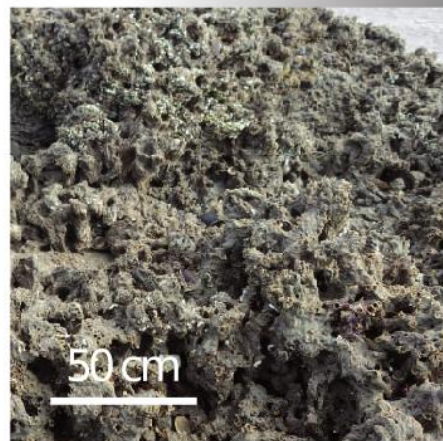
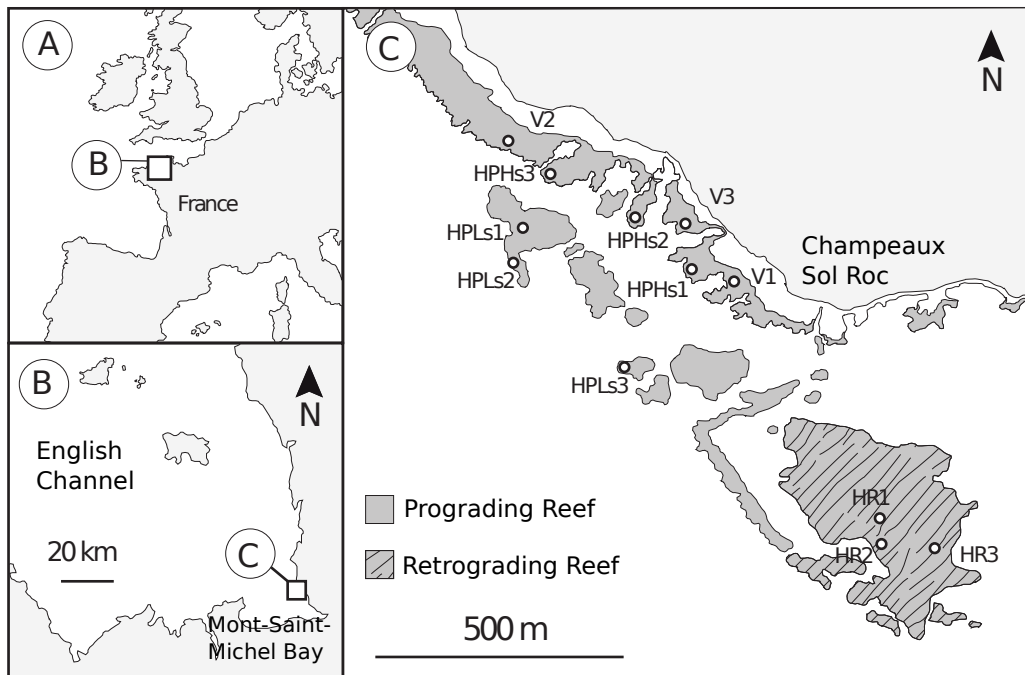
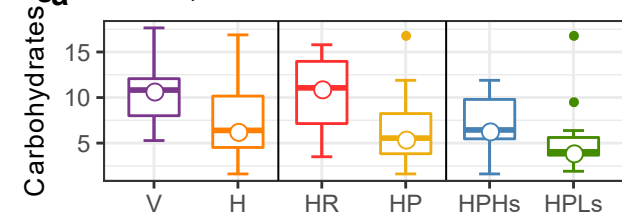
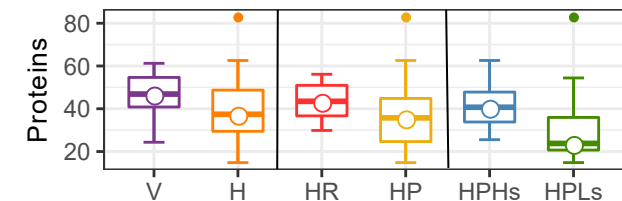
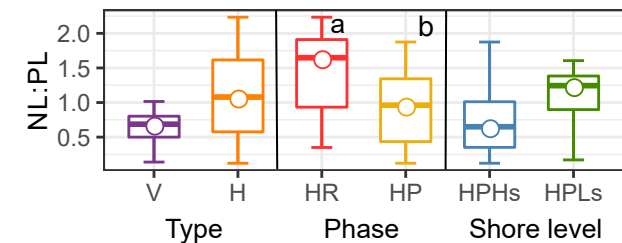
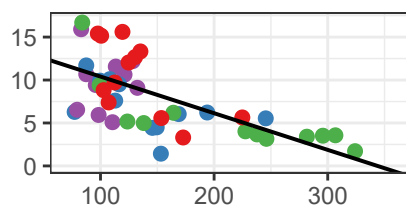
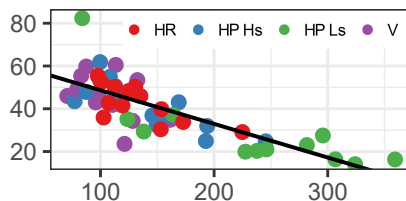
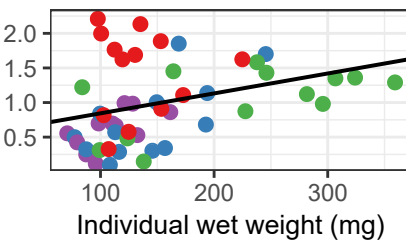
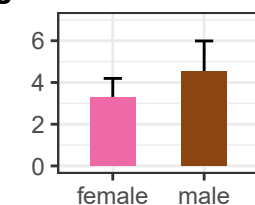
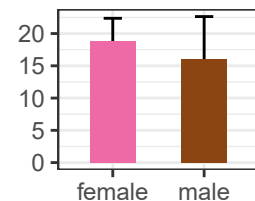
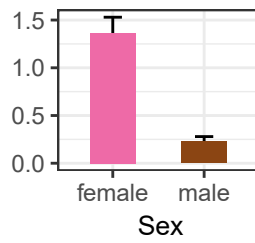


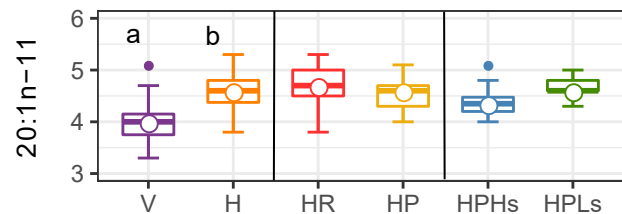
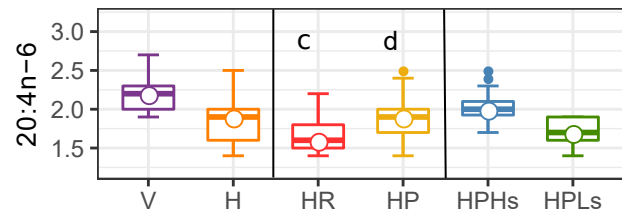
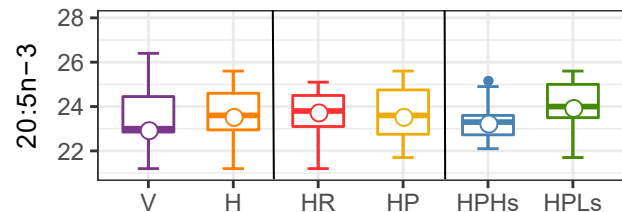
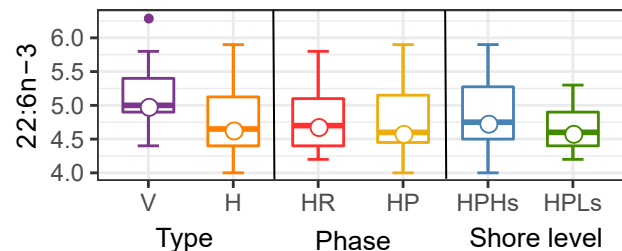
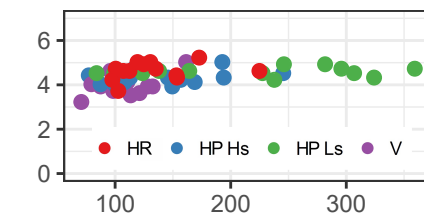
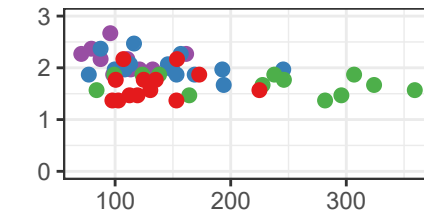
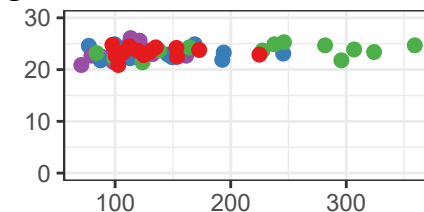
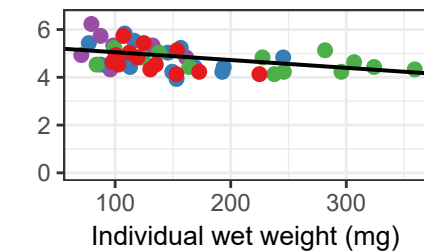
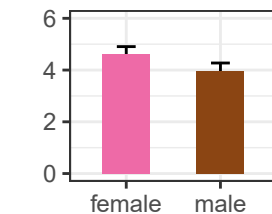
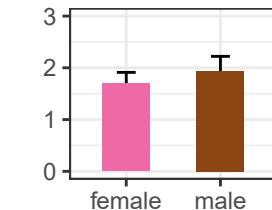
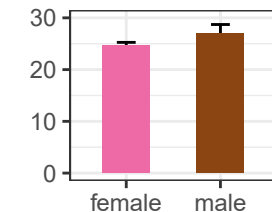
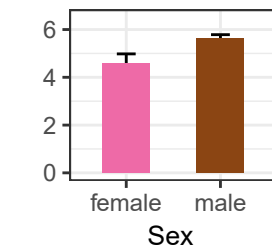


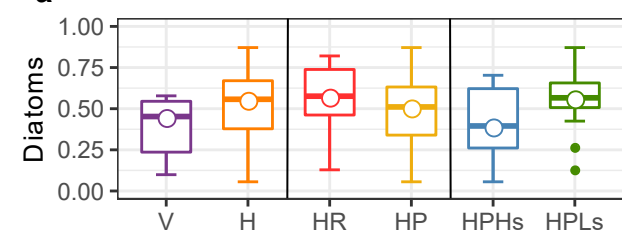
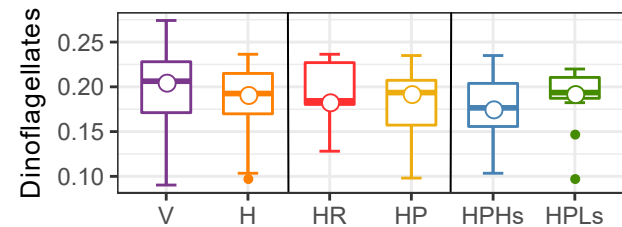
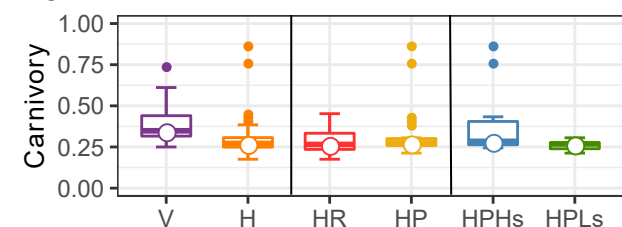
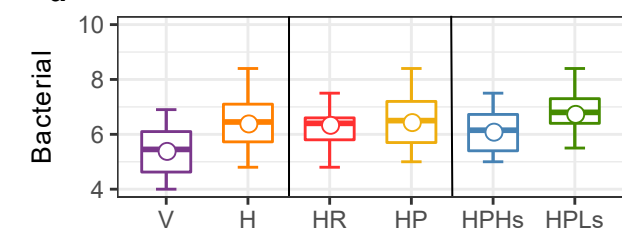
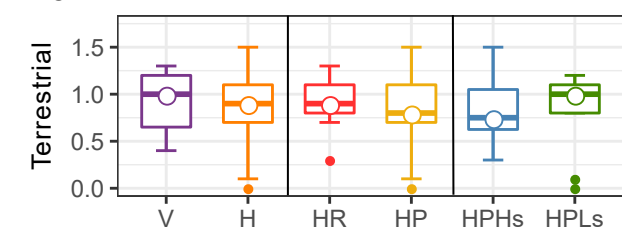
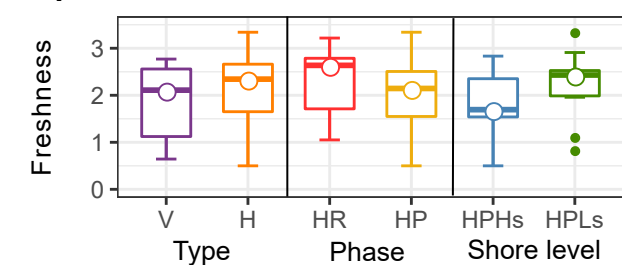
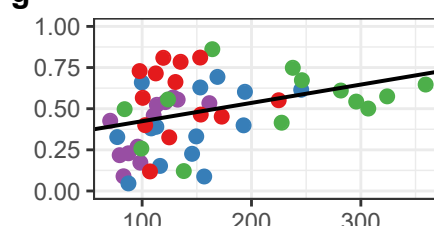
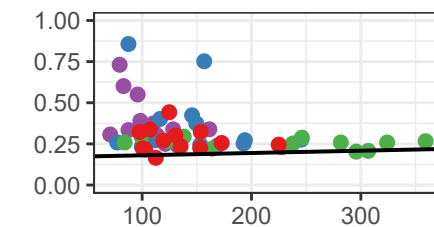
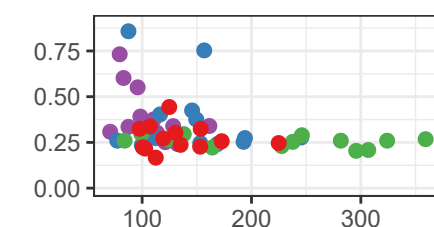
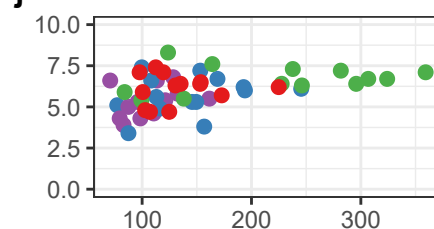
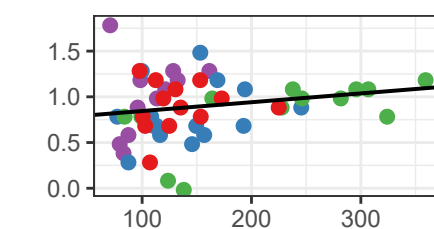
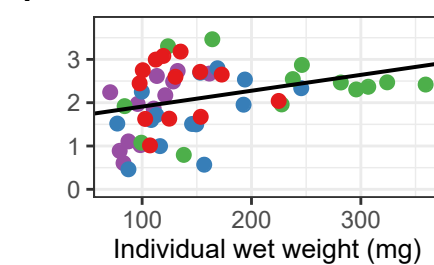
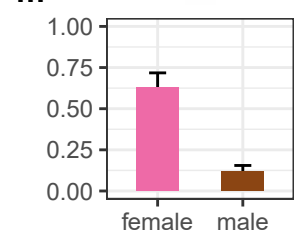
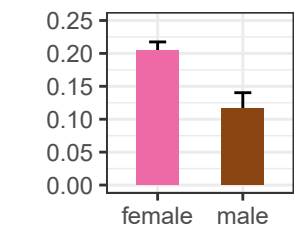
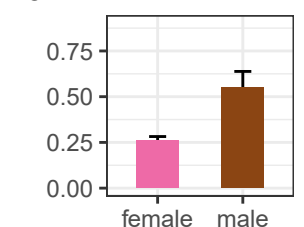
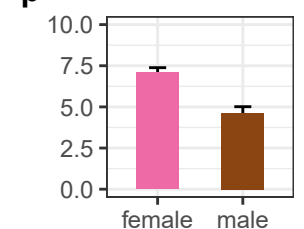
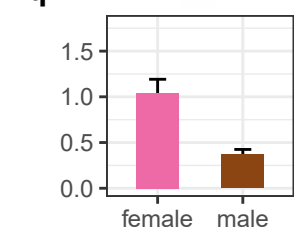
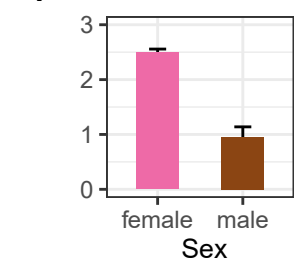
Figure 2

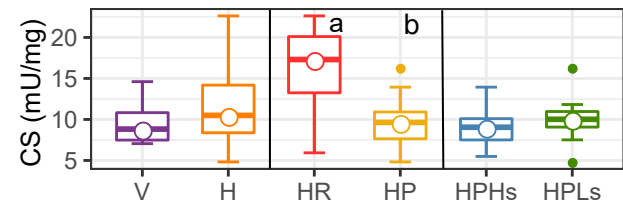
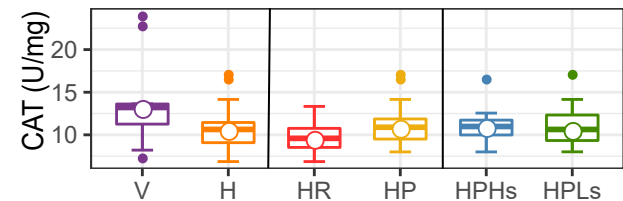
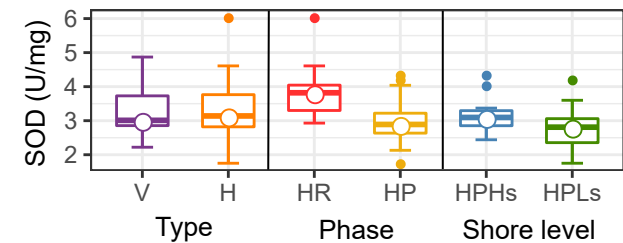
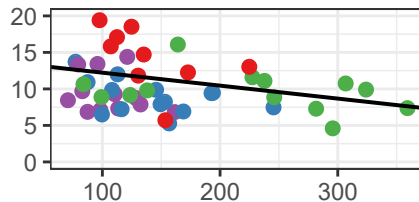
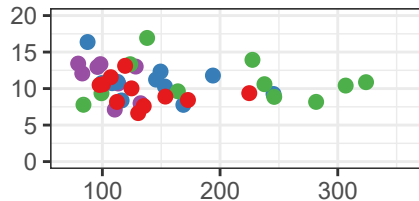
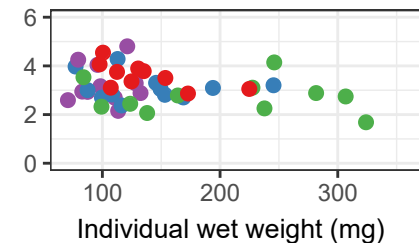
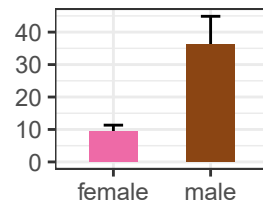
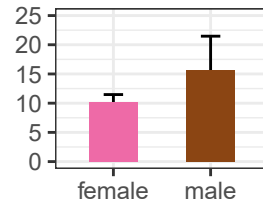
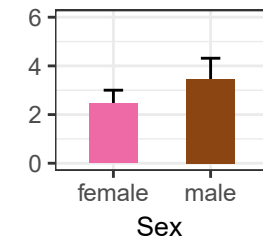




**Figure 3**  $F=1.1$   $p=0.395$ **b**  $F=0.3$   $p=0.799$ **c**  $F=8.0$   $p=0.009^*$ **d**  $F=21.2$   $p<0.001^*$ **e**  $F=52.7$   $p<0.001^*$ **f**  $F=9.9$   $p=0.003^*$ **g**  $F=4.4$   $p=0.280$ **h**  $F=2.7$   $p=0.555$ **i**  $F=14.3$   $p<0.001^*$ 

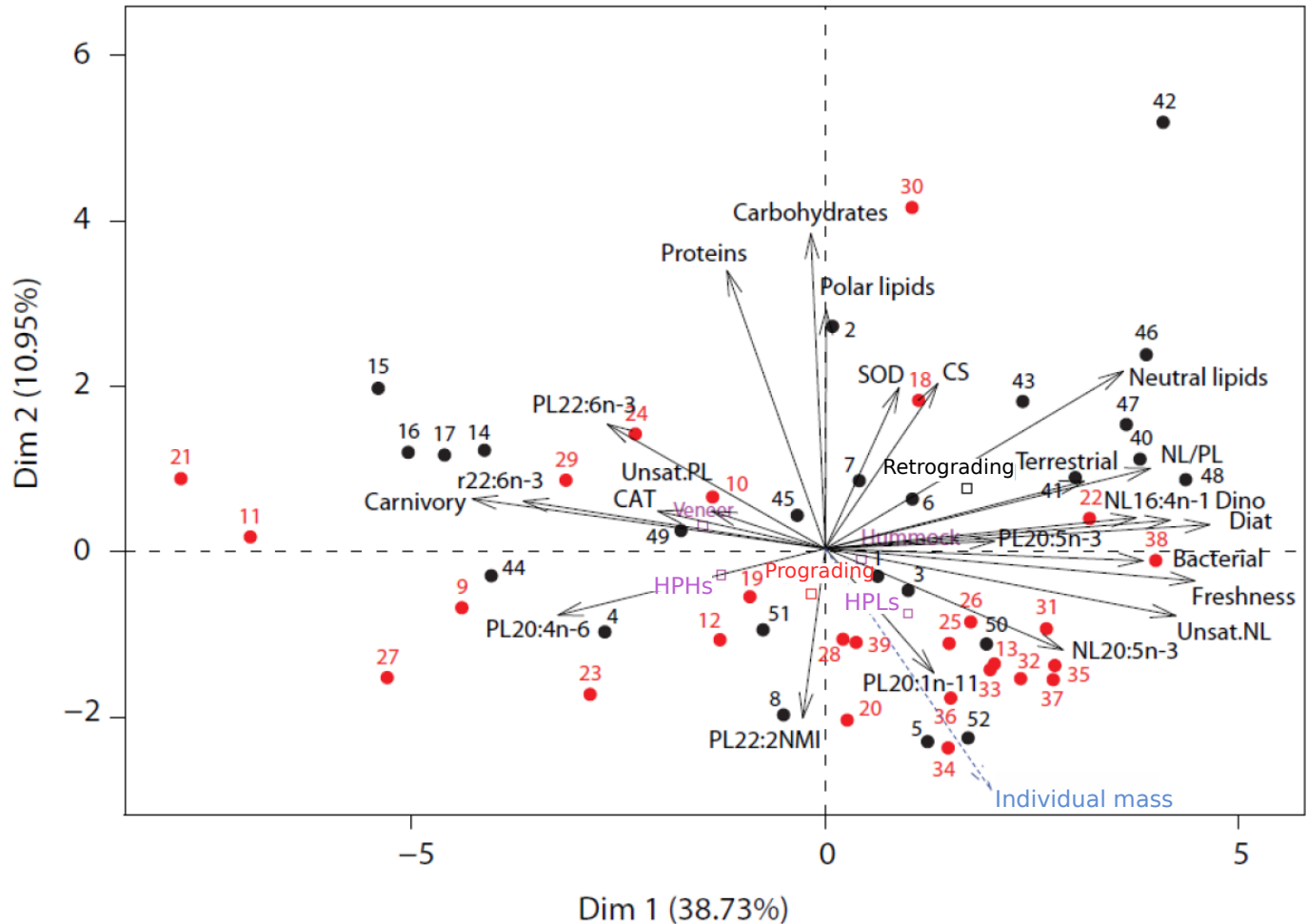
**Figure 4**  $F=6.3$   $p=0.017^*$ **b**  $F=8.0$   $p=0.009^*$ **c**  $F=0.2$   $p=0.913$ **d**  $F=0.8$   $p=0.514$ **e**  $F=2.7$   $p=0.110$ **f**  $F=2.0$   $p=0.167$ **g**  $F=2.0$   $p=0.169$ **h**  $F=7.2$   $p=0.011^*$ **i**  $F=4.1$   $p=0.039^*$ **j**  $F=3.3$   $p=0.303$ **k**  $F=2.4$   $p=0.120$ **l**  $F=5.3$   $p=0.003^*$ 

**Figure 5**  $F=2.2$   $p=0.170$ **b**  $F=1.5$   $p=0.289$ **c**  $F=1.8$   $p=0.225$ **d**  $F=1.0$   $p=0.456$ **e**  $F=2.2$   $p=0.170$ **f**  $F=1.1$   $p=0.399$ **g**  $F=5.7$   $p=0.021^*$ **h**  $F=5.8$   $p=0.021^*$ **i**  $F=2.0$   $p=0.162$ **j**  $F=2.3$   $p=0.141$ **k**  $F=7.9$   $p=0.008^*$ **l**  $F=4.1$   $p=0.050^*$ **m**  $F=5.7$   $p<0.001^*$ **n**  $F=2.7$   $p=0.013^*$ **o**  $F=2.2$   $p=0.024^*$ **p**  $F=3.4$   $p=0.001^*$ **q**  $F=5.5$   $p<0.001^*$ **r**  $F=2.3$   $p=0.003^*$ 

**Figure 6.4**  $p=0.016^*$ **b**  $F=3.1$   $p=0.092$ **c**  $F=3.0$   $p=0.097$ **d**  $F=7.5$   $p=0.009^*$ **e**  $F=0.8$   $p=0.375$ **f**  $F=1.0$   $p=0.335$ **g**  $F=3.4$   $p=0.029^*$ **h**  $F=2.3$   $p=0.251$ **i**  $F=3.9$   $p=0.165$ 

S1\_PCA

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Principal Component Analysis (PCA) biplot of 52 female *Sabellaria alveolata* individuals and 26 biochemical variables. Individual mass is considered as an illustrative quantitative variable, and reef type and phase are considered as illustrative qualitative variables. The first two dimensions of the PCA express 49.68% of the total dataset inertia. Individuals are coloured after their category for the variable “Reef Phase”: progradation phase individuals are in red, retrogradation phase individuals are in black. PCA calculated using the PCA function of the package FactoMineR (Lê et al., 2008).

Lê, S., Josse, J. & Husson, F. (2008). [FactoMineR: An R Package for Multivariate Analysis](#). *Journal of Statistical Software*. 25(1). pp. 1-18