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## Small-scale effects of hydrodynamics on the structure of intertidal macroalgal communities: A novel approach

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### Abstract :

Wave height was used as a proxy to assess the effect of hydrodynamics on the development and structure of intertidal North-East Atlantic rocky macroalgal communities (Brittany). The characterization of hydrodynamics at small-scale (about 10 m) was performed through wave height in situ monitoring using pressure sensors. Both the diversity and the cover of the macroalgal communities were sampled in parallel. Wave heights exhibit large variations with values ranging from ca. 5 cm to 1.60 m. We show that wave height directly controls the cover of macroalgal canopies (Pearson's  $r$  between  $-0.62$  and  $-0.39$ ). In all communities, most of the furoid covers regressed with increasing wave height values. By contrast, positive correlations were found at low shore levels between wave heights and the cover of the kelp *Laminaria digitata* and also of several species of Rhodophyta. Redundancy analysis points out the significant effect of wave height on the inner variability of macroalgal communities, explaining up to 19% of their upright structure and more than 15% of the distribution of canopy-forming groups. In assemblages dominated by either *Pelvetia canaliculata* or *Fucus serratus*, a significant negative correlation was also evidenced with the index of community structure (Ics), which gives an appraisal of both the structure and the development of macroalgal communities. In conclusion, this study provides a novel experimental approach helping to quantify the effects of hydrodynamics on the structure of macroalgal communities using a small-scale in situ quantification of wave heights, revealing hydrodynamics as the main environmental driver of inner structural variations in seaweed assemblages.

### Highlights

► Wave heights have a significant effect on the extent of macroalgal canopies. ► Hydrodynamics explains most of intra-community structural variations. ► *In situ* pressure measurements enable small-scale evaluation of wave heights.

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**Keywords** : macroalgal communities, intertidal zone, rocky shores, wave heights, hydrodynamics, Mini-Diver, Brittany

## 34 **1. Introduction**

35 On rocky shores, the main factors influencing biocenoses distribution are tide and waves  
36 (Menge and Branch, 2001; Bird et al., 2013). Tidal conditions generate various abiotic and  
37 biotic pressures in the intertidal zone (Paine, 1966; Dahlhoff, 2004), inducing vertical  
38 zonation of organisms, which is observed globally (Stephenson and Stephenson, 1949).

39 Rocky shores in the Northern Atlantic are commonly dominated by extensive canopies of  
40 seaweeds, which largely structure the habitat and the associated diversity (Little and Kitching,  
41 1996). Fucooids typically dominate the higher and mid-intertidal zone, while Laminariales  
42 dominate the lower intertidal and high subtidal environments (Lüning, 1990). These intertidal  
43 macroalgae are distributed vertically according to their physiological preferendum, structuring  
44 six successive communities, commonly observed on the coasts of Brittany (Ar Gall and Le  
45 Duff, 2014). The composition and the extent of these communities vary according to several  
46 abiotic factors, including substratum composition, nutrient concentration and hydrodynamics  
47 (Boaventura, 2000; Mieszkowska et al., 2013). However, communities do not necessarily  
48 respond in the same way to similar environmental pressures highlighting the interest of a

49 study based on several well-structured canopies. In that way, the highly diversified megatidal  
50 zone of Brittany constitutes a convenient model for such a study compared to rocky shores of  
51 less extent that are therefore less differentiated (Ar Gall et al., 2016).

52 Hydrodynamics is known to be a major driver of intertidal biocenoses composition (Denny  
53 and Wethey, 2001; Gilman et al., 2006). In the North-East Atlantic, sheltered shores, where  
54 macroalgal canopies are well developed, may be distinguished from exposed shores, where  
55 the presence of these canopies is largely reduced, and where sessile animals (*e.g.* barnacles,  
56 mussels) and limpets dominate the substratum (Raffaelli and Hawkins, 1999). As underlined  
57 by O'Connor et al. (2011), competition for the substratum on rocky shores occurs mostly  
58 between seaweeds and the benthic fauna in wave-exposed sites, whereas sheltered areas are  
59 more influenced by grazing. Some seaweed species are nevertheless well-adapted to wave  
60 exposed rocks, such as *Pelvetiopsis limitata* in the North-East Pacific (Abbott and Hollenberg,  
61 1976) or the variety *linearis* of *Fucus vesiculosus* in the North-East Atlantic (Want et al.,  
62 2014). The effects of hydrodynamics on intertidal organisms is well documented at the  
63 species level, including the decrease of drag coefficient in macroalgae (Gaylord et al., 1994)  
64 and the modification of either their size (Wolcott, 2007) or their morphology (Denny, 2006).

65 Hydrodynamics results from the combined effect of swell and wave action, caused by wind-  
66 induced forces far at sea and driven by tide and currents (Holthuijsen, 2010). Hydrodynamics  
67 in the intertidal zone has first been investigated indirectly through the presence of  
68 characteristic taxa (Ballantine, 1961; Floc'h, 1964; Munda, 1978), which allows a rapid and  
69 costless overview of the shore exposure to waves. However, such approaches, although still in  
70 use because of their simplicity, are limited by local specificities. Alternative methods based  
71 on fetch measurements (*i.e.* the maximum distance swell and waves may travel without  
72 obstacle) have been developed, providing convincing results on the effects of hydrodynamics  
73 on intertidal community structure (Baardseth, 1970; Burrows et al., 2008). Approaches based

74 on wind measurements depend on the local availability of reliable weather data (Thomas,  
75 1986). Predictive models have also been developed to integrate wave energy and / or wave  
76 height at a regional scale (*e.g.* Holthuijsen, 2010; Reguero et al., 2012; Camus et al., 2013;  
77 Guillou and Chapalain, 2015; Rattray et al., 2015). Such models give a framework for local  
78 studies and open up new prospects to determine the effect of waves on the shores (Cefalì et  
79 al., 2016; Puente et al., 2016). Although aforementioned approaches have provided valuable  
80 insights into the relationship between hydrodynamics and intertidal communities, they are of  
81 little use at local scale, where small-scale topography (*i.e.* outcrops, rock orientation, crevices)  
82 can induce a variability in hydrodynamic forces actually affecting benthic habitats (Paine and  
83 Levin, 1981; Helmuth and Denny, 2003; Le Hir and Hily, 2005). Therefore, in order to  
84 characterize the extent of hydrodynamics variability at the metric scale and associated effects  
85 on intertidal biota, direct measurements are necessary. However, such measurements are still  
86 very rare for intertidal environments (Jones and Demetropoulos, 1968; Bell and Denny, 1994;  
87 O'Donnell and Denny, 2008). *In situ* hydrodynamical measurements are generally carried out  
88 using large (>30 cm) pressure transducers in the intertidal zone, including wave height  
89 assessment (Autret et al., 2016; Suanez et al., 2019). Small-size (*ca.* 10 cm) pressure sensors  
90 are currently used to assess water levels and less often tidal variations (Balliston et al., 2018;  
91 Van Putte et al., 2019). In this study, small-size pressure sensors have been used as wave  
92 height recorders on intertidal rocky shores. The relatively low price of these instruments with  
93 regards to the quality of their measurements together with the fact that they can be easily  
94 displayed in the field as a constellation, makes it possible to conduct a detailed study of small-  
95 scale hydrodynamics. Combined to a concomitant accurate evaluation of the structure of  
96 macroalgal communities, this small-scale (*ca.* 10 m) monitoring could provide data to specify  
97 the impact of hydrodynamics at the community level.

98 The working hypothesis of this study is that hydrodynamics would explain most of the inner  
99 variability observed in both the extent and the structure of macroalgal communities. Based on  
100 this hypothesis, three questions may be addressed: (1) in the context macroalgae dominated  
101 rocky shores, is wave height an adequate descriptor/proxy of hydrodynamics? (2) is the small-  
102 scale approach proposed in this study efficient when trying to characterize hydrodynamics at  
103 the community level? (3) do every studied macroalgal communities respond in the same way  
104 to hydrodynamics variations? Thus, the effect of hydrodynamics on both the extent and the  
105 structure of macroalgal communities has been investigated, using *in situ* wave height  
106 measurements, in parallel to the ecological evaluation of six vertically distributed seaweed  
107 assemblages on three rocky shores of Western Brittany.

## 108 **2. Material and methods**

### 109 2.1. Sites and communities

110 Three sites were studied at the western end of Brittany, open to the Atlantic Ocean (Figure 1).  
111 Porsal (48°33.848'N / 4°42.309'W), Porspoder (48°28.876'N / 4°46.293'W) and the Isle of  
112 Segal (48°26.330'N / 4°47.376'W) are about 15 km from each other. Tidal ranges are around 8  
113 m at Spring tides and the sampling sites are 150 - 500 m long and 50 – 200 m wide. These  
114 sites were first selected in order to embrace natural variability from a single coast and  
115 waterbody (in the sense of the WFD). They are relatively sheltered locations with a similar  
116 extensive intertidal vegetation, presenting the six macroalgal communities usually found in  
117 the North-East Atlantic Ocean (Cabioc'h et al., 2014). Macroalgal communities are defined as  
118 assemblages dominated by either one or two structuring Fucales or Laminariales (Ar Gall and  
119 Le Duff, 2014). Communities of the intertidal zone are dominated from top to bottom by: (1)  
120 *Pelvetia canaliculata* (called *Pc* in the text), then (2) *Fucus spiralis* (*Fspi*), both structuring  
121 low (< 30 cm) canopies characterized by a reduced diversity. In the mid intertidal zone two  
122 species are co-dominating (3), *Ascophyllum nodosum* and *Fucus vesiculosus* (*An – Fves*)

123 forming canopies up to 2 m high and more than 50 cm high, respectively. Then, in the low  
124 intertidal zone, (4) *Fucus serratus* (*Fser*) structures a canopy up to 50 cm and (5) *Bifurcaria*  
125 *bifurcata* and *Himanthalia elongata* (*He – Bb*), up to 30 cm for the first one and up to 4 m  
126 high for the second one, are the Fucales co-dominating the lowest level of the intertidal zone.  
127 In the subtidal fringe, (6) the kelp *Laminaria digitata* (*Ld*) forms canopies reaching 3 m high.  
128 Two other kelp species, *Saccharina latissima* and *Saccorhiza polyschides* may be found in  
129 association in this community. The altitude (average tidal height) of these communities was  
130 determined by GIS monitoring and post-treatment with Litto3D® data from the SHOM  
131 (Service Hydrographique et Océanographique de la Marine; diffusion.shom.fr): *P.*  
132 *canaliculata* ( $6.44 \pm 0.39\text{m}$ ), *F. spiralis* ( $5.71 \pm 0.50\text{m}$ ), *A. nodosum* – *F. vesiculosus* ( $4.29 \pm$   
133  $0.72\text{m}$ ), *F. serratus* ( $2.54 \pm 0.46\text{m}$ ), *H. elongata* – *B. bifurcata* ( $1.94 \pm 0.48\text{m}$ ), *L. digitata*  
134 ( $1.32 \pm 0.47\text{m}$ ).

## 135 2.2. Field sampling

136 Field sampling was conducted from late winter to mid spring (January to May 2017). Each  
137 macroalgal community was sampled at low tide, during a one-week period (Table 1). For each  
138 community, thirty-six sampling surfaces or spots (twelve per site), evenly spaced, were  
139 determined by both photographs and GPS positioning. The substratum was mainly bedrock  
140 avoiding microhabitats (*i.e.* crevices, pools, boulders, sediments). For the sampling, a mobile  
141  $1.65 * 1.65$  m plastic grid structure consisting of 25 quadrats of  $33 * 33$  cm was laid on the  
142 spot. Cover was visually determined and classified within five percentage intervals: ]0-5[, [5-  
143 25[, [25-50[, [50-75[ and [75-100]. Two complementary methods were used to estimate the  
144 respective abundances of different algal species (Figure 2). “Undisturbed” sampling aims at  
145 describing the distribution of macroalgal groups during emersion, when thalli are lying on the  
146 substratum, giving a characterization of the canopy-forming species. Only dominating species  
147 of Phaeophyceae and large groups of flora (other Phaeophyceae, erect and crustose



148 Rhodophyta, Chlorophyta) were considered in this method. Macroalgal undisturbed covers  
149 were measured on the area defined by the whole mobile structure (approximately 2.72 m<sup>2</sup>  
150 corresponding to one per spot).

151 “Upright profile” sampling aims at describing both the horizontal and vertical structures of the  
152 macroalgal canopy during immersion. The cover of all seaweed species was estimated based  
153 on the vertical projection of their thalli on the substratum, to mimic their habit at immersion.  
154 Only individuals or patches larger than 5 mm were taken into consideration and classified  
155 within the following four strata: crustose, micro-meibiotic (< 30 cm), macrobiotic (30 – 100  
156 cm) and mega-megalobiotic (> 100 cm). Where necessary, species identification was  
157 undertaken in the laboratory. In this method, the sampled area was defined by the cumulated  
158 surface of three 33cm \* 33cm quadrats randomly chosen within the structure (*i.e.* about 0.33  
159 m<sup>2</sup> per spot).

### 160 2.3. Acquisition and treatment of hydrodynamic data

161 In this study, wave heights were used as a proxy of hydrodynamics and estimated by pressure  
162 sensors. Mini-Diver® sensors (Schlumberger Water Services or SWS) were used to measure  
163 the absolute pressure ( $P_{abs}$ ), equal to the sum of atmospheric pressure ( $P_{atm}$ ) and water  
164 pressure ( $P_{hydro}$ ). A plastic base was screwed to the rock and sensors were additionally fasted  
165 with cable ties; this method proved secure and allowed easy removal after measurements.  
166 They were programmed to record local pressures during seven consecutive days to include  
167 about 12-14 tidal cycles, to span various tidal amplitudes, with a relatively high acquisition  
168 frequency (0.04 Hz for a 25 s period, providing a total of 24000 values). For a given  
169 community, recording was performed by 36 sensors (12 for each site, one per spot),  
170 simultaneously to the sampling of macroalgae.

171 Once recording was achieved, data were downloaded using Diver-Office® (SWS).  $P_{\text{hydro}}$   
172 values were obtained from  $P_{\text{abs}}$  data by subtracting local  $P_{\text{atm}}$ , acquired by a control probe.  
173 Each tide period was treated remotely and a polynomial regression was applied to it in order  
174 to remove the tide oscillation itself and to leave secondary pressure oscillations generated by  
175 waves and globally representative of wave heights. The twenty highest and the twenty lowest  
176 pressure values were then selected to determine the average wave height per tide. This  
177 estimator was proven to be similar to the Significant Wave Height, defined as the mean of  
178 third of the highest waves in the classical wave-by-wave analysis (*e.g.* Holthuijsen, 2010) of  
179 an ancillary, synchronous and co-located signal sampled at a rate in excess of 2 Hz. Since  
180 altitude variations between the sensors within a given community were negligible, average  
181 wave heights were not corrected.

#### 182 2.4. Data treatment and statistics

183 For both types of community sampling (undisturbed and upright profile), medians of  
184 percentage intervals were used to calculate the average cover of taxa or groups of taxa per  
185 community. Data from upright profile sampling were used for the calculation of diversity  
186 indices. The mean species richness was defined as the total number of species / taxa  
187 determined per sampled spot and averaged per community. Furthermore, the Shannon-Wiener  
188 index and the Rhodophyta / Phaeophyceae specific richness ratio (R/P ratio) were calculated  
189 for each sampled spot. The development and structural state of each macroalgal community  
190 was evaluated by the index of community structure (Ics) (Ar Gall and Le Duff, 2014), which  
191 takes into account the cover of taxonomic, stratum and structural / functional groups of  
192 seaweeds. Wave height values were treated after standardization of the variable.

193 All analyses were conducted within the R environment (R Development Core Team, 2014).

194 Both normality and variance homogeneity were first assessed on all biological and physical

195 data sets with Shapiro–Wilk and Bartlett / Levene tests, respectively. Macroalgal community  
196 parameters (diversity, indices) were compared between the three sites using Kruskal-Wallis  
197 (KW) tests. To establish potential correlations between species and variables Pearson's  $r$   
198 coefficients were calculated, using the “corrplot” package (Wei and Wei, 2017). Redundancy  
199 analysis (RDA) was carried out with “vegan” (Oksanen et al., 2013) to determine how  
200 environmental factors influence the development and the structure of macroalgal  
201 communities. Undisturbed sampling or upright profile sampling data were used as response  
202 variables and the latitude, for site position, and average wave heights, for hydrodynamics, as  
203 explanatory variables. Then, an ANOVA and a constrained ordination were applied to  
204 variables of the RDA to determine if the reduced model is significant and, if so, which  
205 explanatory variable is mostly involved. Variation of communities was then partitioned with  
206 respect to both explanatory variables, *i.e.* site and wave height. The relative importance of  
207 each explanatory variable and their degree of interaction were summarized in Venn diagrams.

### 208 **3. Results**

#### 209 3.1. Community structure

210 Within the sampling period in the three sites, 125 macroalgal species were determined  
211 including 15 Chlorophyta, 83 Rhodophyta and 27 Phaeophyceae. Cover of dominating  
212 Phaeophyceae, mean species richness and Ics values are given by community and site in  
213 Table 1. Cover values of dominating Phaeophyceae ranged between *ca.* 45% in *Pc* and 70%  
214 in *An – Fves*, with large intra-community and inter-site variations corresponding to the  
215 heterogeneity of the intertidal canopies. It is the highest at Porsal for the high and middle  
216 intertidal levels and at Porspoder for low intertidal levels (Table 1). Nevertheless, no  
217 significant difference was found between sites. Maximum values of macroalgal mean species  
218 richness for a spot ( $\approx 0.33 \text{ m}^2$ ), *i.e.* 37 species in *Ld* and 34 species in *He – Bb*, were obtained

219 in Segal. The mean species richness did not differ significantly between sites for a given  
220 community, except for *Fspi* and *He – Bb* with higher values at Segal (KW, p-value < 0.05). It  
221 increased from the high intertidal zone to the *He – Bb* community, with a plateau for *Ld*.  
222 Values of the Shannon-Wiener index ranged between 0.2 – 3.0 and those of the R/P ratio  
223 varied between 0.5 and 20.0, suggesting large discrepancies in macroalgal diversity between  
224 communities (significant differences, KW, p-value < 0.05). However, values did not differ  
225 significantly between successive tidal heights (KW, p-value < 0.05). The Shannon-Wiener  
226 index showed higher values in Segal for the *He – Bb* community (KW, p-value < 0.05),  
227 corresponding to a higher mean species richness (see above). KW tests did not reveal any  
228 significant intra-community difference for Ics. Three groups of communities differing  
229 significantly (KW, p-value < 0.05) may be observed (*Pc* and *Fspi* | *An – Fves*, *Fser* and *He –*  
230 *Bb* | *Ld* alone), with increasing values of Ics between these groups.

### 231 3.2. Wave heights

232 Wave heights were calculated for each spot and then averaged per community and per site  
233 (Table 1), according to the procedure and to the periods defined above. Given that recording  
234 periods were different, wave heights were smaller in high level communities than in lower  
235 levels and show a reduced variability between sites. Thus, wave heights ranged from 15 to 25  
236 cm between sites, with an average of  $18.90 \pm 6.66$  cm, in *Pc* and from 23 to 28 cm, with an  
237 average of  $24.28 \pm 6.83$  cm, in *Fspi*. In *An – Fves*, wave heights were greater but show little  
238 fluctuation between sites, ranging from 52 cm to 65 cm, with an average of  $58.93 \pm 15.40$  cm.  
239 For the three lowest communities of the shore, a larger variability occurred in wave heights  
240 between sites, *i.e.* from 94 to 125 cm in *Fser*, from 59 to 135 cm in *He – Bb* and from 45 to 89  
241 cm in *Ld*, with average values per community of  $107.16 \pm 21.72$  cm,  $93.04 \pm 35.96$  cm and  
242  $72.30 \pm 21.77$  cm, respectively. The least exposed site was Porsal, for all communities of the  
243 shore, while Segal was the most exposed site for high level communities and Porspoder for

244 mid and low intertidal communities. Including all recording periods, the maximum value of  
245 wave height obtained in one spot was 158.3 cm, in *He – Bb* at Porspoder, and the minimum is  
246 5.91 cm in *Pc* at Porsal. Considering the spatial distribution of wave heights inside each  
247 community on shorelines up to 250 m, their values may be either randomly distributed or vary  
248 significantly with the distance between sampling spots. The most drastic variation observed  
249 was a doubling of height values between two neighboring spots in *Pc* at Segal separated only  
250 by 8 m, rising from 19 cm to 37 cm. At the opposite, wave heights may only differ slightly  
251 between two spots, like a 12 % discrepancy in *He – Bb* at Porsal, from *ca.* 51 cm to 57 cm, *i.e.*  
252 6 cm over 190 m distance. Wave heights increase towards the open sea in communities with  
253 sampling spots placed on an axis perpendicular to the coastline. On the contrary, when the  
254 axis parallels the coastline, wave height values were distributed randomly.

### 255 3.3. Effects of hydrodynamics on seaweed communities based on undisturbed sampling

256 In order to point out significant factors affecting the structure of seaweed canopies, a  
257 redundancy analysis (RDA) was performed for each community. The constrained ordination  
258 ( $p$ -value < 0.05) on RDA revealed that wave heights influence five out of six macroalgal  
259 communities, and that the site had an impact on the highest and the lowest macroalgal  
260 communities on the shore (Figure 3).

261 Wave height variation explained between 9.0 and 15.8% of the variance for four communities  
262 (*Pc*, *An – Fves*, *Fser*, *He – Bb*). By contrast, site effects never explained more than 2% of the  
263 variance and may be considered as negligible. The interaction between wave height and site  
264 had also a small impact for most of the communities, except *Pc* and *Ld*. For *Ld*, the  
265 contribution of each physical variables was difficult to determine. No significant result was  
266 evidenced for the *Fspi* community, suggesting no effect of site nor wave height on the  
267 community structure.

268 To assess the effect of hydrodynamics in community structure, correlation tests were applied  
269 between wave heights and undisturbed cover data, results shown in Figure 4. Cover of several  
270 dominating Fucales was negatively correlated with wave heights. The highest correlation ( $r =$   
271  $-0.54$ ) was observed for the *Pc* community, whereas correlation coefficients were between  $-$   
272  $0.39$  and  $-0.48$  for mid-to-low intertidal communities. Other Fucales did not show any  
273 correlation, like *F. spiralis* with a  $p$ -value of  $0.84$  in its own community, *F. vesiculosus* with  
274  $p$ -value =  $0.39$  in *An – Fves* and *H. elongata* with a  $p$ -value of  $0.05$  in *He – Bb*. Two opposite  
275 cases were observed with Laminariales structuring the lowest levels (*Ld* community), a  
276 positive correlation with wave heights for *L. digitata* ( $r = 0.39$ ), but a negative one with *S.*  
277 *latissima* ( $r = -0.36$ ). A positive correlation was also observed between wave heights and the  
278 total cover of erect Rhodophyta in the *An – Fves* community ( $r = 0.37$ ) and in *He – Bb* ( $r =$   
279  $0.39$ ), and a negative correlation with the cover of *H. elongata* in the *Ld* community ( $r = -$   
280  $0.44$ ).

#### 281 3.4. Effects of hydrodynamics on seaweed communities based on upright profile sampling

282 Following the same method used for undisturbed sampling, a RDA was conducted on the  
283 covering of all seaweed species. Wave height had an impact on four communities, while the  
284 site factor affects significantly five communities (Figure 5). The variation of the two  
285 explanatory variables partly diverged from the results obtained in the case of the undisturbed  
286 sampling. The range of variation due to wave heights was larger, between  $3.6$  and  $19.1\%$ . The  
287 site effect was globally higher and varies between  $4.1$  and  $17.4\%$ . Unlike the undisturbed  
288 sampling, the *Fspi* community showed a significant response, whereas *An – Fves* did not.  
289 Correlation coefficients were calculated for all seaweed species and for various biological  
290 indices relative to wave heights. Results are summarized in Table 1. The same tendencies  
291 were found in both upright profile and undisturbed samplings for the cover of *P. canaliculata*

292 in *Pc*, *B. bifurcata* in *He – Bb*, *L. digitata* and *H. elongata* in *Ld*, with similar correlation  
293 values (Figure 6). In contrast, no correlation was found with any Fucales in *An – Fves* and in  
294 *Fser*.

295 Considering Chlorophyceae, a negative correlation was evidenced in *An – Fves* and in *Fser*  
296 between the cover of *Cladophora rupestris* and wave heights, with coefficients of -0.46 and -  
297 0.36 respectively.

298 The cover of several erect Rhodophyta appeared to be dependent on wave heights. At  
299 intermediate intertidal levels, *Chondracanthus acicularis* and *Gelidium spinosum* were  
300 positively correlated with hydrodynamics with Pearson's  $r$  of 0.44 and 0.35, respectively. A  
301 similar result was obtained in *He – Bb* for *G. spinosum* ( $r = 0.62$ ), *Ellisolandia (Corallina)*  
302 *elongata* ( $r = 0.40$ ), *Chondrus crispus* ( $r = 0.39$ ), *Gelidium corneum* ( $r = 0.35$ ) and *Ceramium*  
303 *virgatum* ( $r = 0.33$ ).

304 Mean species richness and Shannon index did not correlate with wave heights. However, the  
305 Ics index showed negative correlations at the community level in *Pc* ( $r = -0.42$ ) and *Fser* ( $r =$   
306  $-0.39$ ). In low levels of the shore, correlations were evidenced for the R/P ratio, positive in *He*  
307  $- Bb$  ( $r = 0.41$ ) and negative in *Ld* ( $r = -0.38$ ).

#### 308 4. Discussion

309 Although the existence of a relationship between wave exposure and rocky intertidal  
310 assemblages has been described for a long time (Little and Kitching, 1996), few studies have  
311 addressed this issue beyond the clear contrast opposing sheltered, seaweed-covered shores, to  
312 exposed, less-vegetated ones (e.g. Cabioc'h et al., 2014). The variability of wave exposure  
313 occurring within a shore and its potential impact on inducing small-scale (at the metric scale)  
314 variability in intertidal habitats (e.g. O'Donnell and Denny, 2008) are often overlooked in the  
315 literature. Our study addressed this paradigm on six different macroalgal communities

316 distributed vertically on rocky shores of the Western Brittany coastline, using *in situ* high-  
317 frequency direct monitoring of wave exposure. Therefore, this work provides insights about  
318 this important aspect of intertidal ecology.

319 Correlations between dominating Phaeophyceae and wave height nearly show the same  
320 patterns for undisturbed and upright profile samplings suggesting that both approaches are  
321 pertinent to evaluate the effects of hydrodynamics on macroalgal communities. Thus, negative  
322 correlations occur between the cover of several dominating Fucales and wave height  
323 following both procedures. This result is in agreement with the statement that tearing off  
324 macroalgae by strong hydrodynamics make canopies regress drastically (Ballantine, 1961;  
325 Lewis, 1964; Burrows et al., 2008). As shown in other works (Grenager and Baardseth, 1965),  
326 cover regression affects particularly dominating Phaeophyceae, except for *L. digitata* which is  
327 favored by an increase of wave exposure. In sheltered locations, important sediment deposit  
328 may occur (Ballantine, 1961), limiting the development of large, perennial macroalgae to the  
329 benefit of short-lived opportunistic macroalgae (Daly and Mathieson, 1977). *L. digitata*, for  
330 instance, does not withstand a long burying of its large holdfast under sediments (Ar Gall et  
331 al., 2016). In that way, in low wave exposure, *L. digitata* may be replaced relatively quickly  
332 by *S. latissima* which is more efficient in colonizing unstable substrata (Bunker et al., 2017).  
333 Furthermore, *L. digitata* shows higher growth rates in relatively agitated water (Kregting et  
334 al., 2016). Consequently, the fact that the *Ld* community exhibits a positive correlation  
335 between wave heights and cover of *L. digitata* is not surprising and in agreement with studies  
336 on hydrodynamic tolerant kelps (Starko and Martone, 2016). The lack of correlation between  
337 wave height and the cover of dominating species in *Fspi* might be related to a heatwave in  
338 summer 2016 which resulted in a decrease of *F. spiralis* cover by nearly 70% at Porspoder  
339 (*pers. obs.*). The size of *H. elongata* follows high seasonal variations, with the elongation of  
340 receptacles up to four meters in Spring and their falling down in Autumn (Cabioch et al.,



2014). Such a high seasonality might account for the lack of correlation observed between the cover of that co-dominating species and wave heights in *He – Bb*.

The mean species richness may be a good tool to evaluate the ecological state of a seaweed community (Wells et al., 2007) and was occasionally related to hydrodynamics (Nishihara and Terada, 2010). Although they did not reveal any correlation between macroalgal diversity and hydrodynamics, our results remain consistent with those of Connan (2004) and Ar Gall and Le Duff (2014). Ics values found in this study are similar to those reported by Ar Gall and Le Duff (2014) in all communities. However, in the low shore of Porspoder, Ics scores of *He – Bb* and *Ld* communities are clearly higher (beyond the standard deviation). Besides, other monitoring results from the Rebent (Benthic Network in Brittany) has already shown values exceeding 1.32 for *He – Bb* in seven sites and 1.52 for *Ld* at three sites (Ar Gall and Le Duff, *pers. comm.*). This descriptive index is negatively correlated to hydrodynamics in *Pc* and *Fser* with no significant relationship in other communities, pointing out an irregular effect of waves and swell on both the extension and the structure of macroalgal communities. The absence of a correlation between hydrodynamics and Shannon-Wiener index is probably related to the large dispersion of values. At the opposite, the R/P ratio is positively correlated to wave height in *He – Bb* and negatively in *Ld*, showing that hydrodynamics promotes the predominance of Rhodophyta in *He – Bb*, while it favors Phaeophyceae species in *Ld*.

The variance partitioning shows that hydrodynamics has an effect on most of the studied communities explaining up to 15.8% of the total variance in undisturbed sampling and 19.1% in upright profile sampling. These values are high when considering a single explanatory variable in variance partitioning (*e.g.* Quillien et al., 2015). They tend to confirm the major role of hydrodynamics on intertidal assemblages at local scale (Cefali et al., 2016).

Differences were evidenced between the two sampling approaches when comparing Venn diagrams. Undisturbed sampling is mainly influenced by wave heights, whereas upright

366 profile sampling is also affected by the site explanatory variable. This discrepancy is stronger  
367 in the low intertidal zone, with more contrasted positive and negative correlations with  
368 hydrodynamics. While undisturbed sampling only detects variations in the cover of canopy  
369 forming Phaeophyceae, upright profile sampling gives also information on the effect of wave  
370 exposure on understory species. For instance, positive correlations between wave height and  
371 epilithic turf-forming species like *Chondrus crispus*, *Gelidium spinosum* and *G. corneum*  
372 reflect the fact that Rhodophytes better withstand hydrodynamics thanks to an overall smaller  
373 size than large Phaeophyta in the intertidal zone (Puente et al., 2016). Increasing cover of red  
374 seaweeds may also explain partially the concomitant regression of large Fucales such as *F.*  
375 *serratus* and *A. nodosum*, suggesting a competition between these two functional groups.  
376 Increasing covers due to stronger hydrodynamics is documented so far in the genus *Gelidium*  
377 (Prathep et al., 2009). In the same way, a positive correlation with hydrodynamics is observed  
378 for *Ellisolandia (Corallina) elongata*, a finding already reported from the North of Spain  
379 where *Corallina* spp. dominate intertidal communities (Ramos et al., 2016a). Indeed, the  
380 thallus organization of articulate coralline seaweeds is considered as well adapted to exposed  
381 biotopes (Martone and Denny, 2008). In the case of *Ceramium virgatum*, mostly growing as  
382 epiphyte on other species (Maggs and Hommersand, 1993), the positive correlation may be  
383 associated to the physical damages caused by hydrodynamics to host species, either directly  
384 by wave action, or indirectly by grazing, which both favor the development of epiphytes  
385 (Gaylord, 1999). An indirect relationship between *Cladophora rupestris* and hydrodynamics  
386 may be suspected, since this species grows preferentially under the canopies of *Fucus* spp.  
387 and *A. nodosum* (Brodie et al., 2007), as underlined in our study by a strong correlation with  
388 the cover of Fucales ( $r = 0.68$  in *Fser* and  $r = 0.61$  in *An - Fves*).

389 Wave heights inside a community may vary randomly or follow a coastline – open sea  
390 gradient, depending on the distribution of the sampling spots. Wave heights averaged on three

391 sites vary between *ca.* 19 cm in *Pc* and *ca.* 108 cm in *Fser* with maximal values reaching  
392 around 160 cm. The data presented in our study are consistent with those from previous  
393 studies for assemblages dominated by sessile animals and limpets obtained by *in situ* wave  
394 height recording (O'Donnell and Denny, 2008) or by buoy sensors (Gilman et al., 2006).  
395 However, values are rather low compared to those reported from previous works (e.g. Jones  
396 and Demetropoulos, 1968; Bell and Denny, 1994), probably because these recordings are one-  
397 off measurements. Wave heights differ between communities and so between corresponding  
398 altitudes on the shore, but no statement can be inferred from these data, given that recording  
399 periods are different. To carry out an inter-community study of hydrodynamics, it would be  
400 necessary to monitor pressures simultaneously on a single site. Discrepancies in wave heights  
401 occur also between sites for a single community, a result which may be linked to surrounding  
402 topography and site openness. For example, Porsal is the least exposed site, probably due to  
403 the occurrence of numerous reefs off the coast (more than 30 islets permanently emerged in  
404 all directions within a radius of 4 km from the site).

405 Even though all wave oscillations (usual periods between 6 s and 12 s, versus 25 s in our  
406 study) could not be taken into account in our *in situ* monitoring of hydrodynamics, data  
407 obtained by Mini-Diver® sensors at a frequency of 0.04 Hz ( $T = 25$  s) are coherent with  
408 significant wave heights calculated from values obtained at a frequency of 1 Hz ( $T = 1$  s)  
409 (unpublished personal data), measured by the same sensors within shorter durations (*e.g.* 6 h  
410 versus *ca.* 7 days) and by Wave Gauge OSS1-010-003C-03 sensor (Ocean Sensor Systems  
411 Inc., Coral Springs, USA). Considering the one-week period used to evaluate wave height  
412 exposure, structural differences observed in a given macroalgal community depend on the  
413 hydrodynamic forces conditioning it all year long (Levin and Paine, 1974; Ramos et al.,  
414 2016b). Thus, the spatial study of community structure, relatively to a condensed set of wave  
415 exposure data (here wave heights), may be informative enough about the long-term effect of

416 hydrodynamics. The coherence of the following results suggests the temporal  
417 representativeness of our wave height data: (1) when sampling spots are distributed along a  
418 coastline –open sea transect, wave height values follow a corresponding increasing gradient  
419 (2) sampling spots are numerous enough to consider the micro-topography of the shore at the  
420 intra-community level (3) the average wave height follows site patterns per community.  
421 Considering the above assertions, wave height may be considered as an adequate  
422 descriptor/proxy of local hydrodynamics. In the same way, the small-scale monitoring  
423 performed in this study is efficient to characterize the hydrodynamics at the community level.  
424 However, further experiments should be scheduled to assess the accuracy of our experimental  
425 approach with longer time hydrodynamic regimes (*cf.* Guillou and Chapalain, 2015). Finally,  
426 it would be interesting to compare the trends delineated at the assemblage level by our local  
427 scale wave height proxy to larger scale approaches at the site level, such as fetch  
428 measurements or Baardseth index (Baardseth, 1970; Burrows et al., 2008).

429 The originality of the ecological evaluation of seaweed assemblages carried out in this study  
430 lies in (1) the community approach (Ar Gall et al., 2016) (2) the fine space scale used to assess  
431 hydrodynamics (3) the double (undisturbed and upright profile) sampling analysis. Although  
432 the zonation of communities is well described in the world (Lüning, 1990; Barnes and  
433 Hughes, 1999; Witman and Roy, 2009), and the contribution of hydrodynamics to the  
434 differentiation of seaweed canopies has been partially investigated, an inter-community study  
435 of wave exposure at the site level has still to be achieved. In this prospect, the intra-  
436 community procedure developed in this work may constitute an efficient approach.

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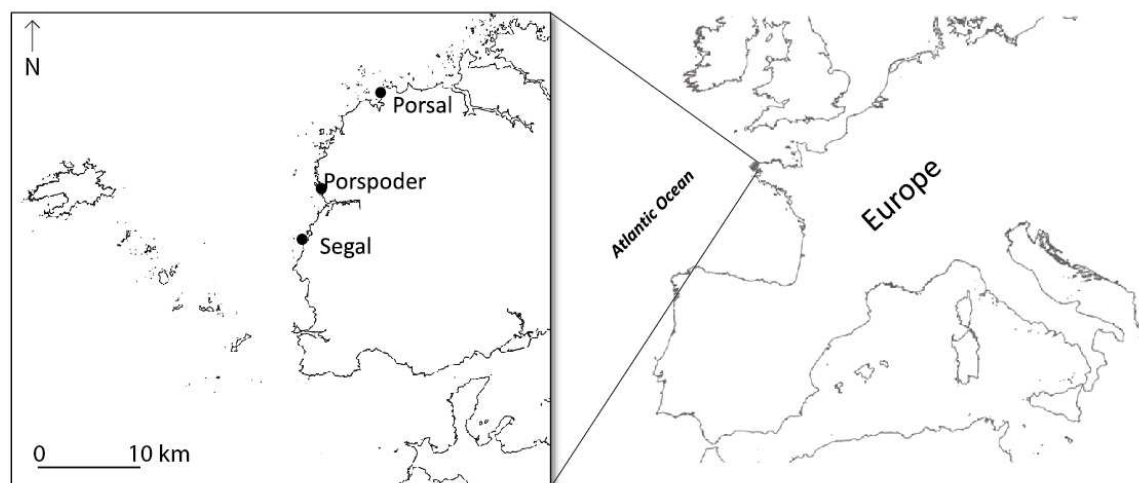


600 *Table 1: Average values and standard deviations of Ics, mean species richness, cover of*  
 601 *dominating Phaeophyceae, average wave heights corresponding recording periods per*  
 602 *community and site. Communities dominated by: Pc = Pelvetia canaliculata, Fspi = Fucus*  
 603 *spiralis, An – Fves = Ascophyllum nodosum – Fucus vesiculosus, Fser = Fucus serratus, He*  
 604 *– Bb = Himanthalia elongata – Bifurcaria bifurcata, Ld = Laminaria digitata.*

| Intertidal level | Community        | Site      | Ics         | Mean species richness | % cover of dominating Phaeophycean | Average wave height (cm) | Wave height / seaweed sampling period |
|------------------|------------------|-----------|-------------|-----------------------|------------------------------------|--------------------------|---------------------------------------|
| High             | <i>Pc</i>        | Segal     | 0.56 ± 0.23 | 5.08 ± 1.24           | 38.13 ± 21.75                      | 24.96 ± 4.91             | 08/05/17 to 14/05/17                  |
|                  |                  | Porspoder | 0.57 ± 0.15 | 4.17 ± 1.03           | 39.38 ± 24.52                      | 16.16 ± 3.41             |                                       |
|                  |                  | Porsal    | 0.56 ± 0.16 | 4.58 ± 1.16           | 54.17 ± 33.63                      | 15.56 ± 6.72             |                                       |
|                  | <i>Fspi</i>      | Segal     | 0.86 ± 0.24 | 13.17 ± 5.10          | 60.21 ± 30.22                      | 27.61 ± 5.21             | 15/02/17 to 22/02/17                  |
|                  |                  | Porspoder | 0.73 ± 0.25 | 7.83 ± 4.45           | 41.45 ± 27.02                      | 23.82 ± 4.88             |                                       |
|                  |                  | Porsal    | 0.87 ± 0.18 | 7.92 ± 2.02           | 60.83 ± 31.34                      | 23.54 ± 9.11             |                                       |
| Medium           | <i>An – Fves</i> | Segal     | 1.12 ± 0.30 | 13.75 ± 6.73          | 61.04 ± 34.70                      | 59.91 ± 8.52             | 12/01/17 to 19/01/17                  |
|                  |                  | Porspoder | 1.07 ± 0.28 | 13.17 ± 3.93          | 75.00 ± 33.51                      | 64.23 ± 20.96            |                                       |
|                  |                  | Porsal    | 1.03 ± 0.52 | 12.17 ± 3.90          | 76.04 ± 26.23                      | 52.64 ± 12.95            |                                       |
|                  | <i>Fser</i>      | Segal     | 1.13 ± 0.23 | 19.25 ± 4.67          | 45.42 ± 27.11                      | 102.04 ± 9.63            | 01/02/17 to 08/02/17                  |
|                  |                  | Porspoder | 0.95 ± 0.29 | 14.42 ± 5.99          | 45.00 ± 34.79                      | 124.66 ± 29.38           |                                       |
|                  |                  | Porsal    | 0.96 ± 0.25 | 15.75 ± 3.96          | 55.21 ± 25.88                      | 94.77 ± 3.81             |                                       |
| Low              | <i>He – Bb</i>   | Segal     | 1.15 ± 0.27 | 30.17 ± 3.71          | 41.46 ± 32.64                      | 84.93 ± 24.61            | 15/03/17 to 22/03/17                  |
|                  |                  | Porspoder | 1.32 ±      | 22.83 ± 3.66          | 57.08 ± 21.50                      | 134.7 ± 17.45            |                                       |

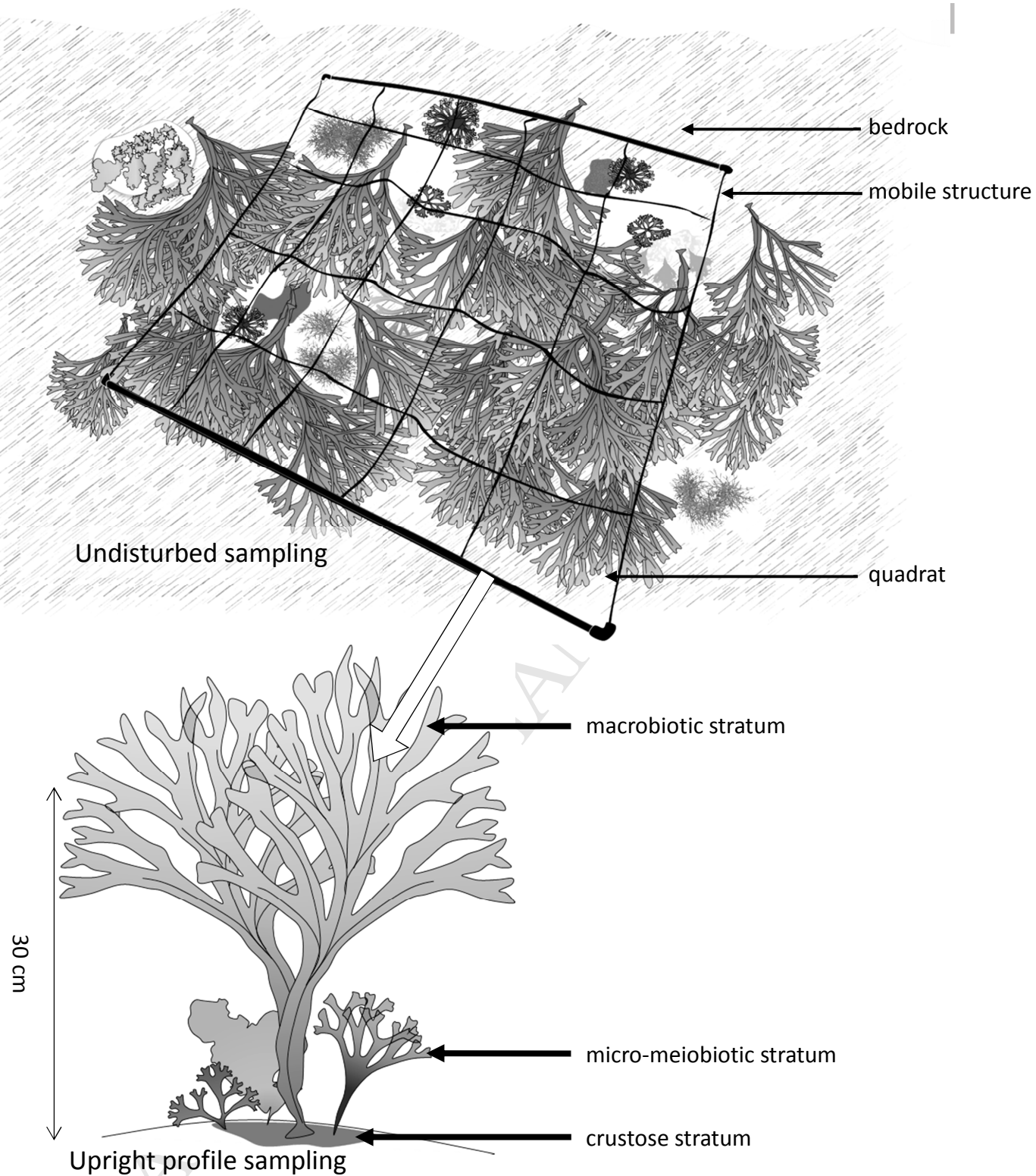
|           |           |                |              |               |               |                         |
|-----------|-----------|----------------|--------------|---------------|---------------|-------------------------|
|           |           | 0.16           |              |               |               |                         |
|           | Porsal    | 1.07 ±<br>0.14 | 23.25 ± 3.28 | 52.71 ± 29.30 | 59.50 ± 3.61  |                         |
|           | Segal     | 1.42 ±<br>0.19 | 25.58 ± 6.24 | 57.82 ± 21.02 | 84.10 ± 13.29 |                         |
| <i>Ld</i> | Porspoder | 1.52 ±<br>0.17 | 21.82 ± 7.39 | 78.18 ± 16.92 | 88.72 ± 8.96  | 31/03/17 to<br>07/04/17 |
|           | Porsal    | 1.42 ±<br>0.19 | 24.17 ± 4.41 | 69.79 ± 20.79 | 45.44 ± 2.78  |                         |

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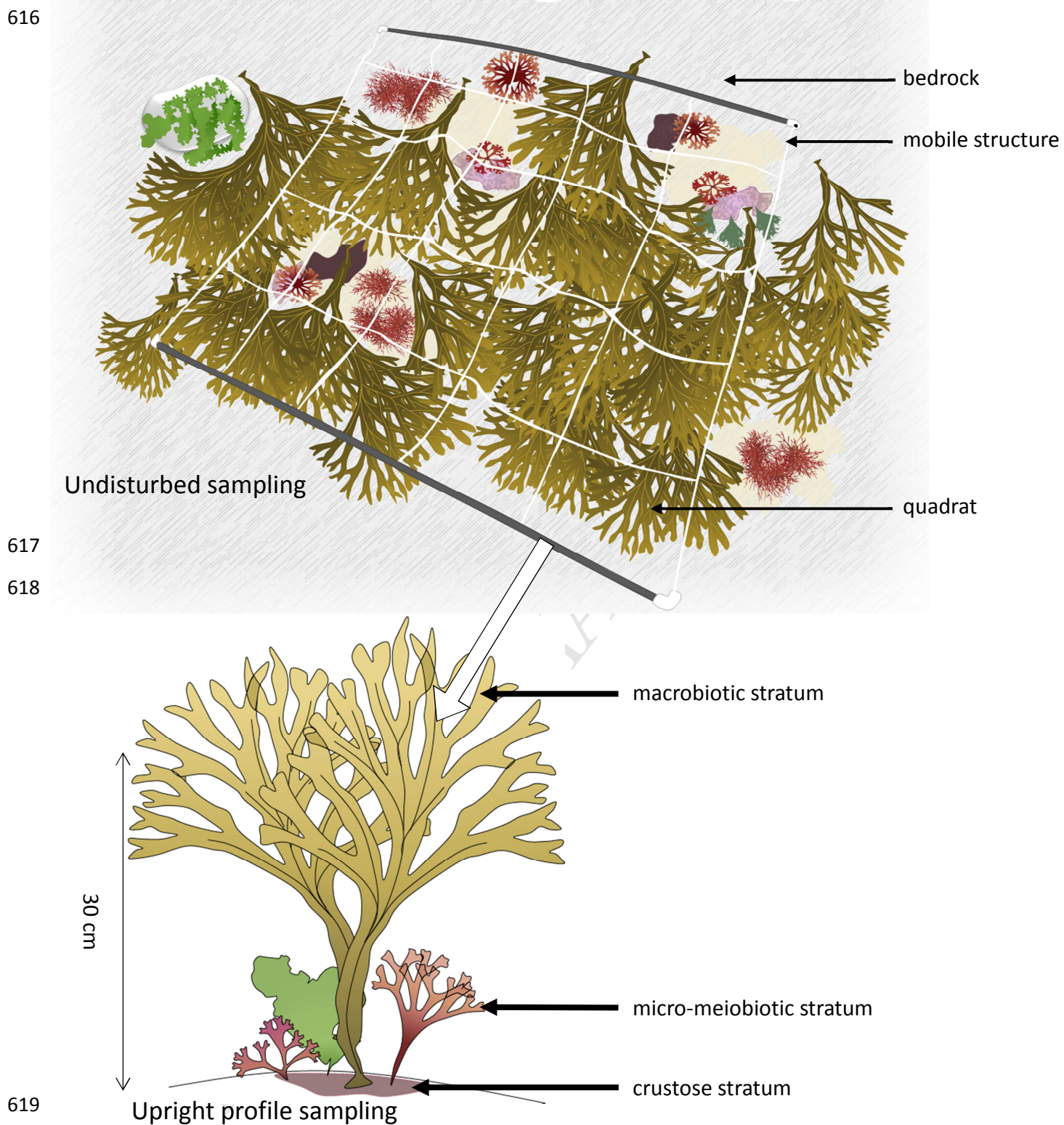
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607 *Figure 1: Location of the three sites on the North-West coast of Brittany*

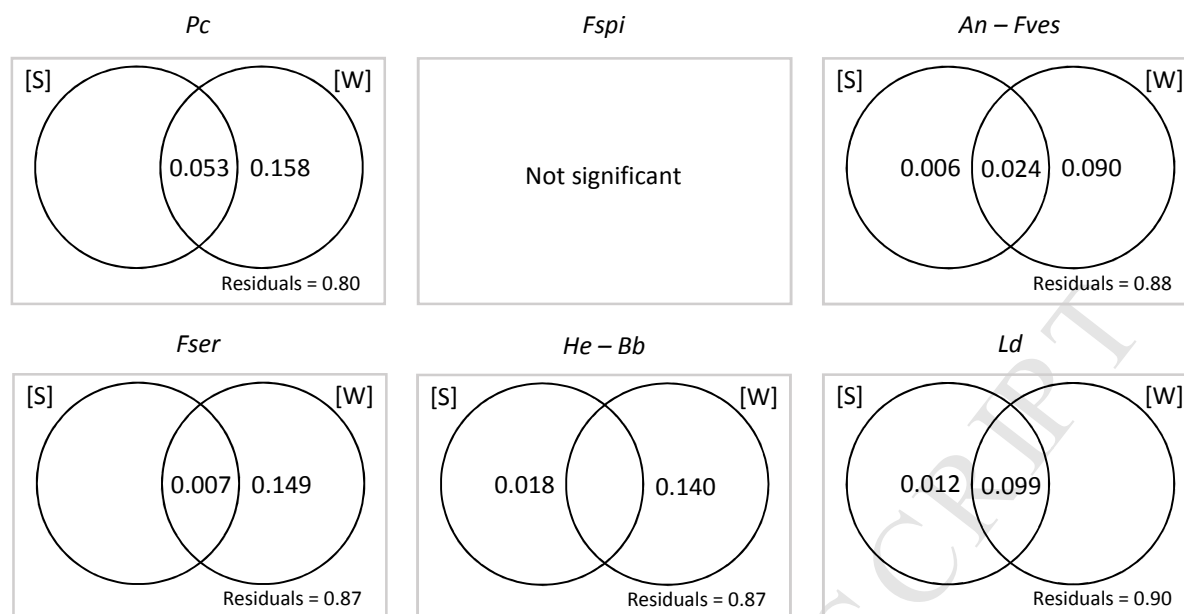


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612 *Figure 2: Description of the two methods of sampling used in the study. Undisturbed*  
 613 *sampling takes into account the major groups of macrophytes on the whole structure. upright*  
 614 *profile sampling is based on a finer description of the macrophytes species and their canopy*  
 615 *and is applied in three quadrats of the structure.*

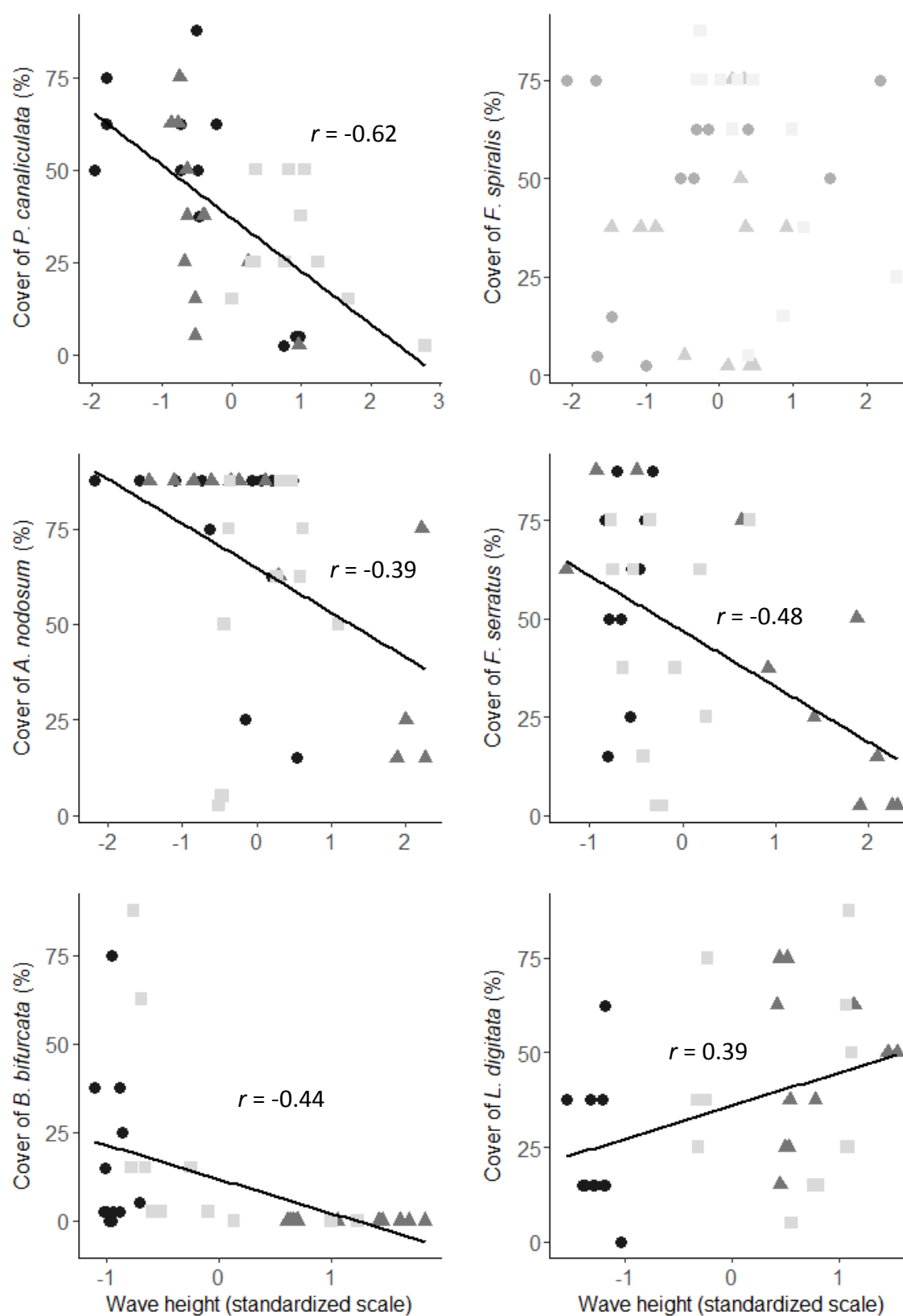


621 *Figure 2: Description of the two methods of sampling used in the study. Undisturbed*  
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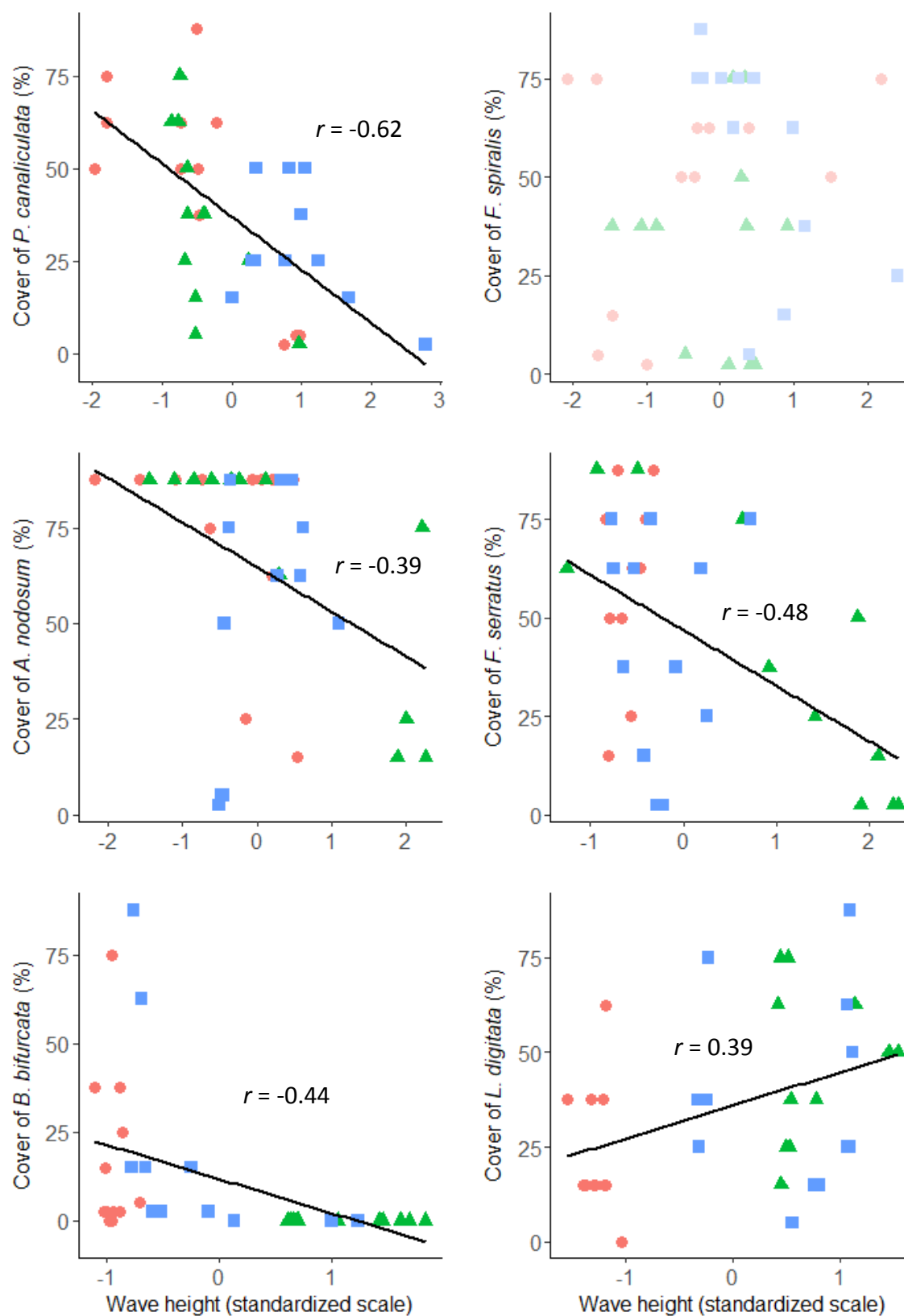
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626 *Figure 3: Venn diagrams illustrating the result of variance partitioning for the undisturbed*  
 627 *sampling, taking into account the undisturbed sampling data (cover of dominating species of*  
 628 *Phaeophyceae, groups of seaweeds), per community with contribution of physical variables.*  
 629 *Contribution of each variable is expressed as a fraction of 1 corresponding to a percentage.*  
 630 *[S]: site, [W]: wave height. Residuals: unexplained variation. Communities dominated by: Pc*  
 631 *= Pelvetia canaliculata, Fspi = Fucus spiralis, An - Fves = Ascophyllum nodosum - Fucus*  
 632 *vesiculosus, Fser = Fucus serratus, He - Bb = Himanthalia elongata - Bifurcaria bifurcata,*  
 633 *Ld = Laminaria digitata.*



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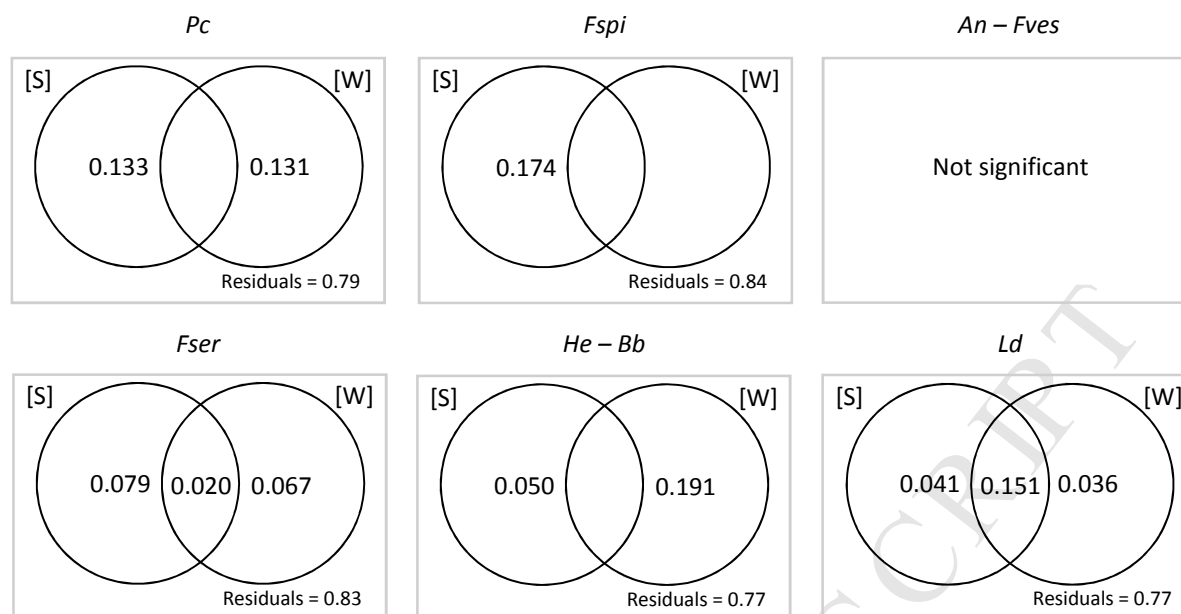
635 *Figure 4: Cover of dominating brown seaweeds in the six studied communities related to*  
 636 *normalized wave heights in the case of the undisturbed sampling method. p-value < 0.05 and*  
 637 *r = coefficient of regression. Sites: ● Porsal, ■ Segal, ▲ Porspoder*



638

639 *Figure 4: Cover of dominating brown seaweeds in the six studied communities related to*  
 640 *normalized wave heights in the case of the undisturbed sampling method. p-value < 0.05 and*  
 641 *r = coefficient of regression. Sites: ● Porsal, ■ Segal, ▲ Porspoder*

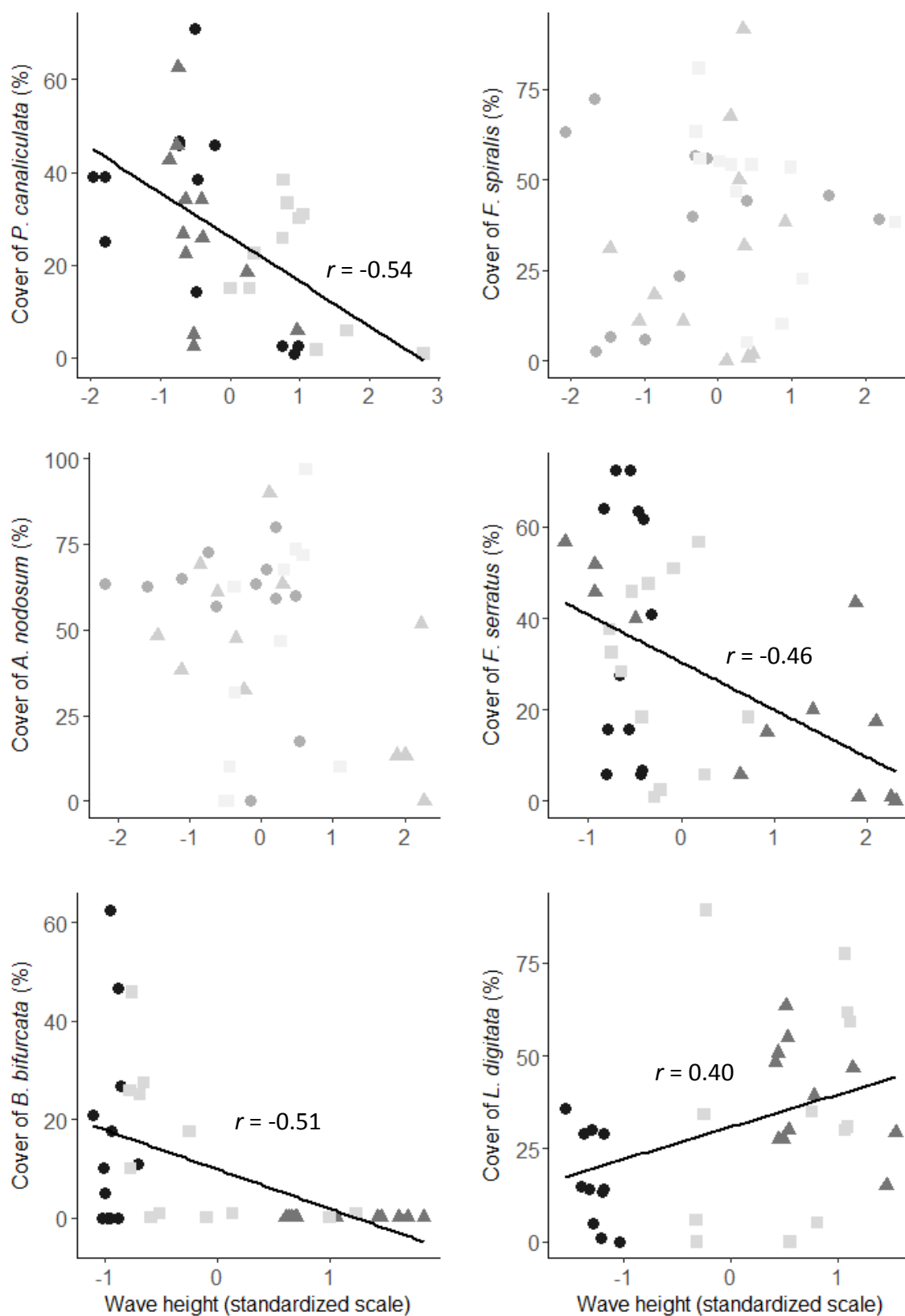




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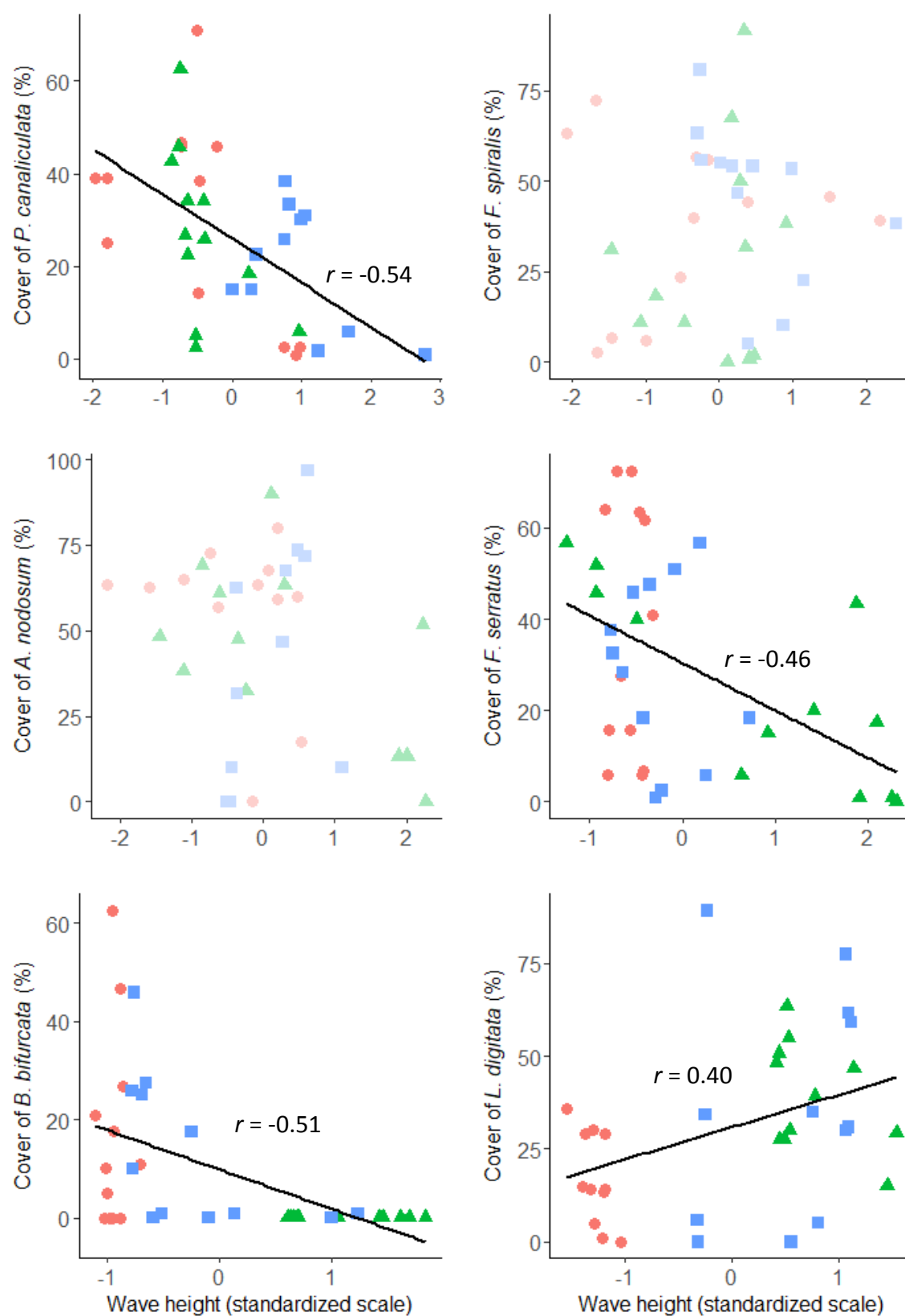
644 *Figure 5: Venn diagrams illustrating the result of variance partitioning for the upright profile*  
 645 *sampling, taking into account the cover of every conspicuous seaweed species found in*  
 646 *quadrats per community with contribution of physical variables. Contribution of each*  
 647 *variable is expressed as a fraction of 1 corresponding to a percentage. [S]: site, [W]: wave*  
 648 *height. Residuals: unexplained variation. Communities dominated by: Pc = Pelvetia*  
 649 *canaliculata, Fspi = Fucus spiralis, An - Fves = Ascophyllum nodosum - Fucus vesiculosus,*  
 650 *Fser = Fucus serratus, He - Bb = Himanthalia elongata - Bifurcaria bifurcata, Ld =*  
 651 *Laminaria digitata.*

652



653

654 *Figure 6: Cover of dominating brown seaweeds in the six communities related to normalized*  
 655 *wave heights in the case of the upright profile sampling method. p-value < 0.05 and r =*  
 656 *coefficient of regression. Sites: ●Porsal, ■Segal, ▲Porspoder*



657  
 658 *Figure 6: Cover of dominating brown seaweeds in the six communities related to normalized*  
 659 *wave heights in the case of the upright profile sampling method.  $p$ -value < 0.05 and  $r =$*   
 660 *coefficient of regression. Sites: ● Porsal, ■ Segal, ▲ Porspoder*

661

Wave heights have a significant effect on the extent of macroalgal canopies.

Hydrodynamics explains most of intra-community structural variations.

*In situ* pressure measurements enable small-scale evaluation of wave heights.

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