

A peer-reviewed version of this preprint was published in PeerJ on 25 April 2016.

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Dobson NC, Johnson ML, De Grave S. 2016. Insights into the morphology of symbiotic shrimp eyes (Crustacea, Decapoda, Palaemonidae); the effects of habitat demands. PeerJ 4:e1926
<https://doi.org/10.7717/peerj.1926>

Insights into the morphology of symbiotic shrimp eyes (Crustacea, Decapoda, Pontoniinae); the effects of habitat demands

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Morphometric differences in the optical morphology of symbiotic palaemonid shrimps can be observed among species symbiotic with different host organisms. Discriminant functional analysis revealed three distinct groups within the species examined. Of these, bivalve symbionts appear to have an eye design that is solely unique to this host-symbiont grouping, a design that spans across multiple genera of phylogenetically unrelated animals. Although some taxonomic effects may be evident, this does not explain the difference and similarities in eye morphology that are seen within these shrimps. Therefore evolutionary pressures from their host environments are having an impact on the optical morphology of eyes however, as indicated by host-hopping events there ecological adaptations occur post host invasion.

1 Insights into the morphology of symbiotic shrimp eyes (Crustacea, Decapoda, Palaemonidae); the
2 effects of habitat demands

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8 **Abstract**

9 Morphometric differences in the optical morphology of symbiotic palaemonid shrimps can be
10 observed among species symbiotic with different host organisms. Discriminant functional
11 analysis revealed three distinct groups within the species examined. Of these, bivalve symbionts
12 appear to have an eye design that is solely unique to this host-symbiont grouping, a design that
13 spans across multiple genera of phylogenetically unrelated animals. Although some taxonomic
14 effects may be evident, this does not explain the difference and similarities in eye morphology
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17 events there ecological adaptations occur post host invasion.

18 1. Introduction

19 Symbiotic palaemonid shrimps are widespread and abundant in Indo-West Pacific reefal habitats,
20 characterised by their affinity to form associations with a wide range of taxa. Until recently these
21 shrimps were in the subfamily Pontoniinae. However in a recent phylogenetic study by De Grave
22 *et al.*, (2015) this subfamily was synonymised with the family Palaemonidae, as were the related
23 families Gnathophyllidae and Hymenoceridae. For the purposes of this investigation and
24 throughout the remainder of this paper, we will refer to this group of shrimps as “pontoniine
25 shrimps to avoid any systematic ambiguity. Members of the previously separate families
26 Gnathophyllidae and Hymenoceridae were not included in the present analysis. Within the
27 pontoniine shrimps, an estimated 60-70% (De Grave, 2001) are known to form associations with
28 corals, sponges, ascidians, gorgonians, and so on. However this is likely to be an underestimate
29 as the host association remains unknown for several species, but is inferred to be symbiotic due to
30 their morphological similarity to other species. Pontoniine shrimps occur in a wider variety of
31 tropical and subtropical habitats, and are known from deeper water, down to about 2000 m
32 (Bruce, 2011). However, their highest species richness is on tropical coral reefs, down to about
33 100 m. The most recent catalogue (De Grave & Fransen, 2011) lists 602 species, but numerous
34 species have been described since then.

35 The traditional view of these shrimps as symbionts, has recently been challenged for a number of
36 species dwelling in sponges, where diet studies revealed them to be parasites as their stomachs
37 only contained host tissue and spicules (Ďuriš *et al.*, 2011). At present it is not known how
38 widespread parasitism is in the group, and we thus refer to them as associates, inferring no
39 trophic interaction with the host.

40 Morphological adaptation to an associated mode of life has been extensively noted in the
41 taxonomic literature for pontoniine shrimps. Such adaptations include modified pereopods
42 (Bruce, 1977; Patton, 1994) in addition to extensive modifications in general body plan and
43 mouthparts (Bruce, 1966; Ďuriš *et al.*, 2011). Additionally, a range of ecologies are recognised,
44 ranging from internally dwelling in small sized hosts like ascidians (e.g. species of the genus
45 *Periclimenaeus*) to fish cleaning species, dwelling on anemones (e.g. *Ancylomenes* spp.). Despite
46 this wealth of morphological and ecological disparity, few studies have been done linking
47 morphological disparity with ecological constraints. A recent exception to this is the study by
48 Dobson *et al* (2014) which examined gross eye morphology across four, broad, lifestyle

49 categories: ectosymbionts, bivalve endosymbionts, non-bivalve endosymbionts and free-living.
50 Their results clearly demonstrated considerable differences in superficial optical parameters
51 across various lifestyles. In many decapods, vision is thought to be an important feature of their
52 morphology with variations in morphology and structure reflecting ecological habitat demands
53 (Johnson, Shelton and Gaten, 2000). Differences in eye size, facet size and interommatidial angle
54 have been observed in many marine species occupying different depths (Gaten, Shelton, and
55 Herring, 1992; Johnson *et al.*, 2000). Eye parameter (EP) has been used by a number of
56 researchers as a measure of determining the equipose between sensitivity and resolution of
57 different organisms (Snyder, 1979; Stavenga & Hardie, 1989; Kawada *et al.*, 2006). For
58 organisms occupying well-lit habitats EPs of between 0.45 and 1 rad- μm have been recorded, 1-2
59 for crepuscular and 2-3 for nocturnal species (Kawada *et al.*, 2006), however these values many
60 vary in aquatic organisms due to the different refraction index of water. Pontonine shrimps are
61 ideal study organisms for the relationship between eye morphology, vision and habitat demands,
62 given their predilection for forming associations with a wide range of taxa.
63 The current study builds upon this previous work, by focussing on and contrasting across actual
64 host identities using a multivariate analytical framework and thus aims to further unravel
65 potential differences in gross optical morphology of pontonine shrimps.

66 2. Methods

67 Optical characteristics of 96 species from 40 genera were examined from collections at the
68 Oxford University Museum of Natural History. A copy of the dataset used in this paper can be
69 accessed in the Supplemental Information. The work described in this paper was reviewed and
70 approved by the Department of Biological Sciences, Faculty of Sciences ethics committee
71 approval number U053. To understand differences in eye morphology between host categories,
72 each species was classed into host-symbiont predefined groupings based on their most common
73 host associations (Bruce, 1994); i.e. Actiniaria, Ascidiacea, Asteroidea, Bivalvia, Crinoidea,
74 Echinoidea, Gorgonacea, Hydrozoa, Ophiuroidea, Porifera and Scleractinia or considered to be
75 free-living. For all species, eye span (ES), diameter at the base of the eyestalk (DBES), facet
76 diameter (FD) and eye diameter (ED) were measured using a dissecting microscope fitted with an
77 ocular micrometer. To reduce scaling effects ES, DBES and ED were standardised by post orbital
78 carapace length, whilst FD was standardised by eye diameter. A composite variable, ES-DBES
79 (eye span minus diameter at base of eyestalk), was also formulated to provide an indication of

80 eye mobility, the greater mobility of the eyes the larger the value. In addition to the variables
81 measured, eye parameter (EP) was calculated as an outcome of facet diameter (μm) (FD) and
82 interommatidial angle ($\Delta\phi$ in radians) using Snyder (1979) equation (Equation 1).

83 Equation 1.
$$EP = FD \Delta\phi$$

84 Interommatidial angle in radians, used in the calculation of EP, was estimated using an adaptation
85 of Stavenga's (2003) formula (Equation 2).

86 Equation 2.
$$\Delta\phi = 2 \left(\frac{FD}{ED} \right)$$

87 The presence or absence of the nebenaugae (see Dobson *et al.*, 2014) was also noted and when
88 present the relative size was expressed after standardisation by eye diameter (ED). Our
89 terminology follows Johnson *et al.*, 2015 who utilised nebenaugae for the structure previously
90 referred to under several names.

91 Eye Parameter (EP) and standardised nebenaugae size was compared between hosts using a
92 Kruskal Wallis test in the Statistical Software Package R 3.0.2 as this allowed for *Post Hoc*
93 comparisons (R Core Team, 2013), whilst Eye Diameter (ED) was analysed by the means of an
94 ANOVA.

95 Subsequently, the dataset was analysed with Discriminant Function Analysis (DFA), also known
96 as Multiple Discriminant Analysis (MDA) or Canonical Variate Analysis (CVA). DFA extracts
97 linear combinations of variables (known as roots) which maximise differences amongst a priori
98 defined groups, in this case host categories, with the percentage correctly classified providing a
99 goodness of fit measure, akin to more traditional P values.

100 As DFA requires the number of predictor variables to be fewer than the sample size of the
101 smallest group, a number of host-categories could not be included in the analysis, namely
102 Echinozoa, Hydrozoa, Ophiurozoa and Asterozoa, all of which are relatively infrequently
103 inhabited by pontonine shrimp. Outliers were identified using within host category linear least-
104 squares regression analysis, using post-orbital carapace length as the independent variable.

105 Individual outliers were corrected by re-measurement (where possible), and only excluded from
106 the final dataset if their values still exceeded 3 standard deviation in residual plots. The final
107 dataset analysed with DFA thus comprised of 83 species, across 7 host categories, as well as free-
108 living taxa. Host categories herein analysed, comprise of Actiniaria (9 shrimp species),
109 Ascidiacea (7), Bivalvia (12), Crinoidea (8), Gorgonacea (7), Porifera (14) and Scleractinia (13).
110 Thirteen micro-predatory species, which are currently considered not to be host associated, i.e.
111 free-living were also included in the analysis, a combination of species living on coral reefs and
112 in seagrass beds.

113 For consistency, statistical analysis of eye size, Eye Parameter and nebenaugae was carried out on
114 the reduced dataset.

115 Prior to DFA, proportions were arcsine-transformed to meet the assumptions for statistical
116 analysis of normality and homogeneity (Zuur, Ieno and Elphick, 2010). All DFA analysis was
117 performed in SPSS 18. In all DFA analysis, all variables were entered simultaneously, with the
118 contribution of each variable assessed on the basis of discriminant loadings (structure
119 correlations, rather than discriminant coefficients, as those are considered more valid when
120 interpreting the relative contributions of each variable).

121 **3. Results**

122 **3.1 Eye size, Eye Parameter and nebenaugae presence**

123 Across all species examined, mean relative ED (Fig. 1) ranged from 0.09 to 0.27, with
124 significantly smaller eyes occurring in bivalve associated species (ANOVA, $F_{7,75} = 9.26$, $P < 0.001$,
125 Tukey $P = 0.05$). Although the analysis deemed none of the remaining differences to be
126 statistically significant, ascidian ($\bar{x} = 0.19$, $SD \pm 0.06$) and sponge symbionts
127 ($\bar{x} = 0.19$, $SD \pm 0.06$) were also found to possess some of the smallest relative EDs whilst
128 gorgonian symbionts ($\bar{x} = 0.28$, $SD \pm 0.11$) and free-living shrimps ($\bar{x} = 0.26$, $SD \pm 0.06$) had
129 the largest relative EDs.

130 Eye parameter (EP) (Fig. 2) ranged from 0.44 – 8.06 rad- μm , with a significantly larger EP found
131 in ascidian, bivalve and sponge associates (Kruskal Wallis, H (adjusted for ties) = 43.62, $df = 7$,
132 $P < 0.001$, *Post hoc* pairwise comparisons $P = 0.05$). The smallest EP values were found in
133 associates of crinoid, gorgonians and in free-living shrimps. Associates of sea anemones and
134 corals were not significantly different to any other host category in terms of EP (Fig. 2), whilst
135 the widest range of values is present in sponge associates. Although not statistically considered as
136 outliers in within-host category regression analysis, three species exhibited an aberrant EP, all of
137 the genus *Pontonia*. *Pontonia panamica* an ascidian commensal has the largest EP in the dataset
138 (EP = 7.45), whilst *P. mexicana* and *P. pinnophylax* exhibited considerable larger values than
139 other species associated with bivalves.

140 A significant association was found between the presence/absence of the nebenaug and host
141 category (Chi-squared test, $\chi^2 = 24.777$, $df = 7$, $P < 0.001$). High absence rates of the nebenaug
142 were observed among ascidian, bivalve and poriferan symbionts (Fig. 3), whilst it is prevalent in
143 sea anemone associates and free-living shrimps. However, the relative size is not different across
144 host categories (Kruskal Wallis test, $H = 8.93$, $df = 6$, $P = 0.178$), with ascidians excluded as only
145 one species, *Periclimenaeus hecate*, had a nebenaugen.

146 3.2 Multivariate analysis

147 Discriminant function analysis revealed only two significant roots (Table 1), which cumulatively
148 explain 94.6% of total variance. Examination of the structure matrix (Table 2) revealed that three
149 variables were highly loaded on to the first root (EP, FD, ED), whilst a fourth variable (ES-
150 DBES) displayed greatest loading on the second function.

151 A classification matrix indicates that overall 50.6% of shrimp species were correctly classified in
152 respect to their priori defined groups (host classification) (Table 3), but with significant variation
153 as to within-group classification. Bivalve associates were 100.0% correctly classified, with a high
154 number also correctly classified for sponge associates (78.6%). Over half of the free-living
155 species (61.5%) were correctly classified to their priori group, with other species classified as sea
156 anemone, crinoid and coral associates. Gorgonian associates correctly classified in 42.9% of
157 cases, with misclassified taxa allied to free-living, coral and crinoid associates. Coral associates
158 correctly classified in 38.5% of cases with species misclassifying as associates of sponges, sea

159 anemones, crinoids and free-living species. Sea anemone and crinoid associates were only 22.2
160 and 25.0% correctly classified. All ascidian symbionts were found to misclassify, with 71.4% of
161 them misclassified as sponge associates.

162 When comparing the relative position of the centroids for each host category (Fig. 4) it is
163 obvious, that the eyes of ascidian and sponge associated species are very similar to each other, as
164 are the eyes of crinoid and coral associates, both of which also group with the free-living species.
165 Although broadly similar to the latter grouping, the eyes of gorgonian and sea anemone
166 associates are somewhat divergent as well as divergent to each other, as evidenced by the position
167 of their centroids. Bivalve associates clearly occupy an isolated position, relative to the other
168 host categories.

169 When plotting only the ascidian associates in the DFA analysis (Fig. 5), a divergent position of *P.*
170 *panamica* is evident, whilst the other taxa form a loose grouping. The positions of sponge
171 associates (Fig. 6) reveal two distinct, but loose groupings, as well as a divergent species,
172 *Thaumastocaris streptopus*. Membership of either of the two groups does not appear influenced
173 by phylogeny, as either group contains species belonging to the genera *Typton* and
174 *Periclimenaeus*. The positions of the individual bivalve associates (Fig. 7) reveals a relatively
175 tight grouping, but with an isolated position occupied by *Conchodytes nipponensis*. The
176 positions of individual crinoid associates (Fig. 8) are rather scattered, but with a very isolated
177 position for *Laomenes nudirostris*. A similar scattered pattern is observed for the coral associates
178 (Fig. 9) and the free-living species (Fig. 10). Gorgonian associates also demonstrate this pattern
179 (Fig. 11), but with a significant, isolated position for *Pontonides loloata*. A similar pattern is
180 observed for sea anemone associates (Fig. 12), with an isolated position for *Periclimenes*
181 *scriptus*.

182 4. Discussion

183 Multivariate analysis clearly reveals that three distinct eye types are present in pontoniine
184 shrimps, with bivalve associates comprising a type on their own. Sponge and ascidian associates
185 have remarkably similar eyes, to the point that the majority of ascidian associates were
186 misclassified as sponge associates in the analysis. A third eye type is present in a range of

187 ectosymbiotic taxa, associated with sea anemones, gorgonians, corals, crinoids, as well as free-
188 living species.

189 An examination of the structure loadings reveals that along the first root, both facet diameter
190 (FD) and Eye Parameter (EP) increases, but with a concomitant decrease in eye diameter (ED),
191 whilst along the second root eye mobility (as measured by ES-DBES) decreases. Broadly
192 speaking, the ectosymbiotic and free-living taxa thus have smaller facet diameters, a lower EP
193 and bigger eyes, than their endosymbiotic counterparts in bivalves, sponges and ascidians.
194 Equally, bivalve associates display more mobile eyes than ascidian and sponge associates, but
195 with roughly similar facet diameter and EP. It should be noted that the relative eye size of
196 bivalve associates is significantly smaller than all other host groupings, this may be as a result of
197 their comparably larger body sizes (e.g. mean average 6.9 mm CL versus 3.0 mm CL for
198 Actiniaria, 2.5 mm CL for Porifera and 1.34 mm CL for Gorgonacea symbionts).

199 Within deep sea caridean species the nebenauge has been suggested to have an important role in
200 diurnal migrations (Johnson *et al.*, 2015). The concept that orientation to light is aided by the
201 presence of the nebenauge is further supported by these results with it being highly abundant
202 within sea anemone, crinoid, free-living and coral associates. However for bivalve, ascidian and
203 sponge associates both diurnal migrations and orientation to light would be of little significance
204 for species with an endosymbiotic mode of life.

205 This result is not surprising, given the clear relationship between gross eye morphology of
206 pontonine shrimps and life style already demonstrated in Dobson *et al.* (2014). Therein, based on
207 a range of optical parameters, the eyes of free-living and ectosymbiotic species were found to be
208 very similar, and clearly different from both types of endosymbiotic species considered, bivalves
209 and non-bivalve associates. Further, bivalve endosymbionts exhibited an intermediary group
210 between free-living/ectosymbionts and non-bivalve endosymbionts, potentially linked to their
211 presumed more active lifestyle, with bivalve associated documented to move hosts in search of a
212 mate (Baeza *et al.*, 2011).

213 Whilst the relationships between optical parameters and lifestyle in Dobson *et al.* (2014) appears
214 clear-cut and supported by the present analysis, by including actual host identity, rather than
215 lifestyle in the current analysis, a number of surprising findings emerge.

216 The eyes of ascidian associated species emerges as being remarkable similar to the eyes of
217 sponge associated species, to the point that the majority of a priori classified species in this group
218 were misclassified as sponge eyes by the multivariate analysis. This is herein interpreted being
219 likely a significant signal of phylogenetic constraint, as four out of the seven species in this host
220 category belong to a primarily sponge dwelling genus, *Periclimenaeus* (see below) with generally
221 conservative eye morphology, potentially indicative of recent host switching event(s). Two
222 further species in this host category, phylogenetically unrelated to *Periclimenaeus*, *Dactylonia*
223 *okai* and *Odontonia katoi* are thought to be closely related species (Fransen, 2002), but with
224 significantly different gross eye morphology. *Dactylonia okai* possesses stout triangular shaped
225 eyes, whereas the eyes of *Odontonia* species are small and hemispherical (Fransen, 2002).
226 Whilst *D. okai* and *O. katoi* are found living within large solitary ascidians, species of
227 *Periclimenaeus* are found living within both ascidians and sponges. Species such as
228 *Periclimenaeus orbitocarinatus* and *Periclimenaeus ascidiarum* live in association with
229 compound ascidians that are structurally similar in morphology to the canals of sponges occupied
230 by, for example, *Periclimenaeus maxillulidens*. The structural similarity in hosts between the
231 symbionts of compound ascidians and sponges could be a plausible explanation for the high
232 misclassification of ascidian symbionts to sponges. Two species were misclassified as either a sea
233 anemone or bivalve associate. Although DFA does not provide information on individual
234 classified species, it is evident from Fig. 5 that *P. panamica* is the species misclassified as a
235 bivalve associate. The genus *Pontonia* comprises of 11 species (De Grave & Fransen, 2011) and
236 is morphologically very conservative. Although the host for one species, *P. longispina*, is not
237 known, the majority of species associate with bivalves in the families Pinnidae and Pteriidae,
238 whilst one poorly known species *P. chimaera*, is thought to be an associate of large gastropods of
239 the genus *Strombus*. *Pontonia panamica* is the only species to associate with ascidians, the
240 solitary species *Ascidia interrupta* in the eastern Pacific. Although Marin and Anker (2008)
241 speculate that a host switch to ascidians occurred early on in the evolutionary history of this
242 genus, the retention of essentially a “bivalve” eye is perhaps indicative of a more recent host
243 switching event. However, on balance the differences in eye morphology between the
244 phylogenetically not related genera herein analysed as ascidian associates suggests that despite
245 occurring in a similar host environment, their enclosure inside ascidians has not provided
246 pressure on their eyes to become optically similar. As to whether this lack of overall evolutionary
247 pressure is imparted by distinctive host morphologies (compound, solitary) or habitats (intertidal,

248 subtidal) or indeed is determined by differential behavioural attributes (social biology) of the
249 associates themselves remains unclear.

250 Notwithstanding their close similarity to ascidian associate eyes, the eyes of sponge associated
251 species appear to be quite uniform, with the majority being correctly classified in their a priori
252 defined host group, but seemingly forming two distinct subgroups in the analysis, in addition to
253 the outlying *T. streptopus*. We infer here that the classification into two subgroups is putatively
254 related to host morphologies, as sponge species exhibit a discrete and distinct range of canal
255 sizes. Space partitioning, as well as individual host selection is indeed known to play a
256 significant role in the sponge-dwelling gambarelloides group of *Synalpheus* (Duffy, 1992;
257 Hultgren and Duffy, 2010; 2012). The speculation that canal sizes of the host may play a
258 significant role in optical acuity of pontoniine species, can however not be substantiated, as the
259 host range of most species remains unknown, with even the identity of many hosts simply not
260 being known. For instance, for many species of *Periclimenaeus*, a primarily sponge associated
261 genus, the hosts are not known (Bruce, 2006). Of particular interest are the three ectosymbiotic
262 species included in this primarily endosymbiotic group in the present analysis, *T. streptopus*,
263 *Periclimenes harringtoni* and *Periclimenes incertus*. *Thaumastocaris streptopus* is an Indo-
264 Pacific species, which dwells in the central atrium of vase-shaped sponges like *Siphonochalina*
265 and *Callyspongia* (see Bruce, 1994). Based on the present suite of optic parameters, this species
266 does not cluster with the rest of the sponge associates. Although Āuriš *et al.* (2011) consider the
267 species to be parasitic, in common with several other sponge associates, the isolated position of
268 the species in the present analysis, combined with their asymmetrical first pereopods and a
269 segmented carpus (both unique within the family) is indicative perhaps of a different behavioural
270 niche. The Indo-Pacific, *P. incertus* dwells on the outside of a variety of sponges, and clusters
271 reasonably close to the other sponge associates in the present analysis, potentially indicative of
272 similar relationship to the host, if external. The Caribbean *P. harringtoni* dwells in the atria of
273 *Neofibularia nolitangere* and based on the optical parameters studied herein, appears to have an
274 eye structure very similar to that of endosymbiotic species, potentially an example of habitat
275 driven adaptation, despite the significant difference in position on the host.

276 The sea anemone associates included in the present analysis, fall into four ecological/systematic
277 groups, *Ancylomenes* and three different species groups of *Periclimenes*. *Ancylomenes* species are
278 on the whole considered to be fish cleaners, who only utilise the sea anemone as an advertisement

279 for their services to client fish (Huebner & Chadwick, 2012). It should be noted that this is
280 potentially a generalisation, as direct observation of fish cleaning behaviour is not available for
281 all species, with this information lacking for one species herein included *A. tosaensis*.
282 *Periclimenes yucatanicus* and *Periclimenes rathbunae* are active large bodied species, associated
283 with a variety of sea anemones in the Caribbean. Fish cleaning has not been observed for either
284 species, with Limbaugh *et al.*, (1961) considering *P. yucatanicus* a fish-cleaning mimic.
285 *Periclimenes ornatus* and *P. inornatus* belong to the same species complex, and are smaller
286 bodied species which hide in between the tentacles of a variety of Indo-Pacific sea anemones.
287 Finally, *P. scriptus*, a Mediterranean and subtropical Northeast Atlantic species which is not
288 phylogenetically closely related to the other two groups, is an active species, associated with long
289 tentacle sea anemones, with no known fish cleaning behaviour. With the exception of *P. scriptus*
290 (see below) these species exhibit a scattered grouping in the DFA analysis, and as a group have a
291 low percentage correctly classified, at 22%. It thus appears that despite their broad ecological
292 niche similarity as sea anemone associates, insufficient convergent pressure on their optical
293 parameters is noted, indicative of differential usage of their eyes.

294 In contrast to sea anemone associates, coral associates exhibit a reasonable level of correctly
295 classified in the DFA analysis, at 38.5%, despite the large variety of host morphotypes involved
296 in this association. Several species *Coralliocaris* spp., *Harpilius* spp. and, *Harpiliopsis* spp. are
297 associated with branching corals of the families Pocilloporidae and Acroporidae. Other species
298 in this group are associated with corals which extend their polyps during the day, either short
299 polyps (e.g. *Hamopontonia corallicola* on *Goniopora*) or long polyp forms, such as *Cuapetes*
300 *kororensis* on *Heliofungia actiniformis*. Morphologically heavily modified taxa are also present
301 in this group, such as the laterally flattened *Ischnopontonia lophos* which moves between the
302 corallites of *Galaxea*. It thus appears that the habitat and/or behaviour in the case of coral
303 associates is a significant driver in optical parameters, akin to the free-living species, which had
304 an approximately similar level of correctly classified species (53.8%). However, in contrast to
305 free-living taxa, which are considered to be micro-predators, several of the coral associates are
306 potentially parasites (Stella *et al.*, 2011). The common functionality of their optic parameters (to
307 a degree) remains unclear, although it is known that several species, e.g. *Coralliocaris* defend
308 their coral host against predators (Marin, 2009a; Stella *et al.*, 2011), perhaps necessitating the
309 need for similar optical acuity to free-living micro predators.

310 Bivalve associates exhibited a 100% correct classification in the DFA analysis, although with
311 reasonable scatter in the scatter plot, and a significant outlier (*C. nipponensis*). Yet the group
312 consists of several genera, including *Conchodytes* and *Anchistus*, which are phylogenetically
313 distant (Kou *et al.*, 2014). Furthermore these species can be differentiated by general bauplan
314 morphologies, ranging from relatively unspecialized (*Anchistus* and *Paranchistus* for example) to
315 dorso-laterally compressed (e.g. *Conchodytes*) (Bruce 1981; Fransen & Reijnen, 2012). Their
316 phylogenetic distance is evidence of multiple host invasions (Kou *et al.*, 2014), but the present
317 analysis reveals considerable convergence in optical parameters, indicative of profound habitat
318 induced restraints.

319 A number of species occupy isolated positions within their respective groups, notably *P. loloata*,
320 *P. scriptus*, *C. nipponensis* and *L. nudirostris*. Although we cannot discount variation in optical
321 parameters of individual eyes, which may have lowered the percentage correctly classified and
322 induced a higher degree of scatter, two species are worthy of further discussion. The corneal part
323 of the eye of *Laomenes* species is characterised by an apical papilla (see illustrations for several
324 species in Marin, 2009b) which contains functional facets, but which are somewhat different in
325 shape to facets elsewhere on the cornea. The relative size as well as the exact position of the
326 papilla has been used as a minor taxonomic character to differentiate between species (Marin,
327 2009b). However, it is known that a large degree of infra-specific variation is present, which
328 unquestionably would influence some of the herein included optical parameters. *Periclimenes*
329 *scriptus* appeared isolated within the sea anemone grouping however due to the small size of the
330 specimen (CL 1.25 mm) it is possible that this animal was not fully mature as ovigerous females
331 have a reported CL of 5.0 mm (Đuriš *et al.*, 2013).

332 5. Conclusion

333 Overall, our analysis demonstrates that there is a significant evolutionary pressure of the host
334 environment on the optic parameters of associate shrimp species, with in many cases congruence
335 being evident between phylogenetically unrelated taxa. This is especially evident in bivalve and
336 sponge associates, and to a lesser extent in other host taxa. This result is in sharp contrast to the
337 disparate morphology of many other body parts of pontoniine shrimps, with significant variation
338 in mouthparts, pereopods and even general body shape between genera, inhabiting the same
339 host. At the same time, evidence emerges from the optical analysis of recent host switching

340 events in certain lineages, where the optical parameters have not evolved to a communality yet,
341 especially in the genera *Periclimenaeus* and *Pontonia*, where taxa living in different hosts appear
342 to retain a close optical similarity to those living in other taxa.

343 6. Acknowledgements

344 We would like to thank Dr Sue Hull for her valuable suggestions with regards to the analysis and
345 comments on previous versions of the manuscript. We would also like to thank both reviewers for
346 their valuable comments on the manuscript.

347 7. References

- 348 Baeza, J.A., Bolaños, J.A., Hernandez, J.E., Lira, C. & López, R. 2011. Monogamy does not last
349 long in *Pontonia mexicana*, a symbiotic shrimp of the amber pen-shell *Pinna carnea* from
350 the southeastern Caribbean Sea. - Journal of Experimental Marine Biology and Ecology
351 **407**(1): 41–47.
- 352 Bruce, A.J. 2011. A new record of *Periclimenes pholeter* Holthuis, 1973 (Crustacea: Decapoda:
353 Pontoniinae) from the Red Sea. - Cahiers de Biologie Marine **52**(1): 119–120.
- 354 Bruce, A.J. 2006. *Periclimenaeus nielbrucei* sp. nov. (Crustacea: Decapoda: Pontoniinae), a new
355 sponge associate from the Capricorn Islands, Queensland, with notes on related
356 *Periclimenaeus* species. - Zootaxa **1224**: 1–22.
- 357 Bruce, A.J. 1994. A synopsis of the Indo-West Pacific genera of the Pontoniinae (Crustacea:
358 Decapoda: Palaemonidae). - Theses Zoologicae **25**: 1–172.
- 359 Bruce, A.J. 1981. Notes on some Indo-Pacific Pontoniinae, XXXVI. *Pontonia ardeae* sp. nov., a
360 new bivalve associate from the Capricorn Islands (Decapoda, Natantia). - Crustaceana **40**(2):
361 113–126.
- 362 Bruce, A.J. 1977. The hosts of the coral associated Indo-West Pacific Pontoniine shrimps. - Atoll
363 Research Bulletin **205**: 1–19.
- 364 Bruce, A.J. 1966. Notes on some Indo-Pacific Pontoniinae. XI. A re-examination of *Philarius*
365 *lophos* Barnard, with the designation of a new genus, *Ischnopontonia*. - Bulletin of Marine
366 Science **16**(3): 584–598.
- 367 Dobson, N.C., De Grave, S. & Johnson, M.L. 2014. Linking eye design with host symbiont
368 relationships in pontoniine Shrimps (Crustacea, Decapoda, Palaemonidae). - PloS ONE **9**(6):
369 e99505.

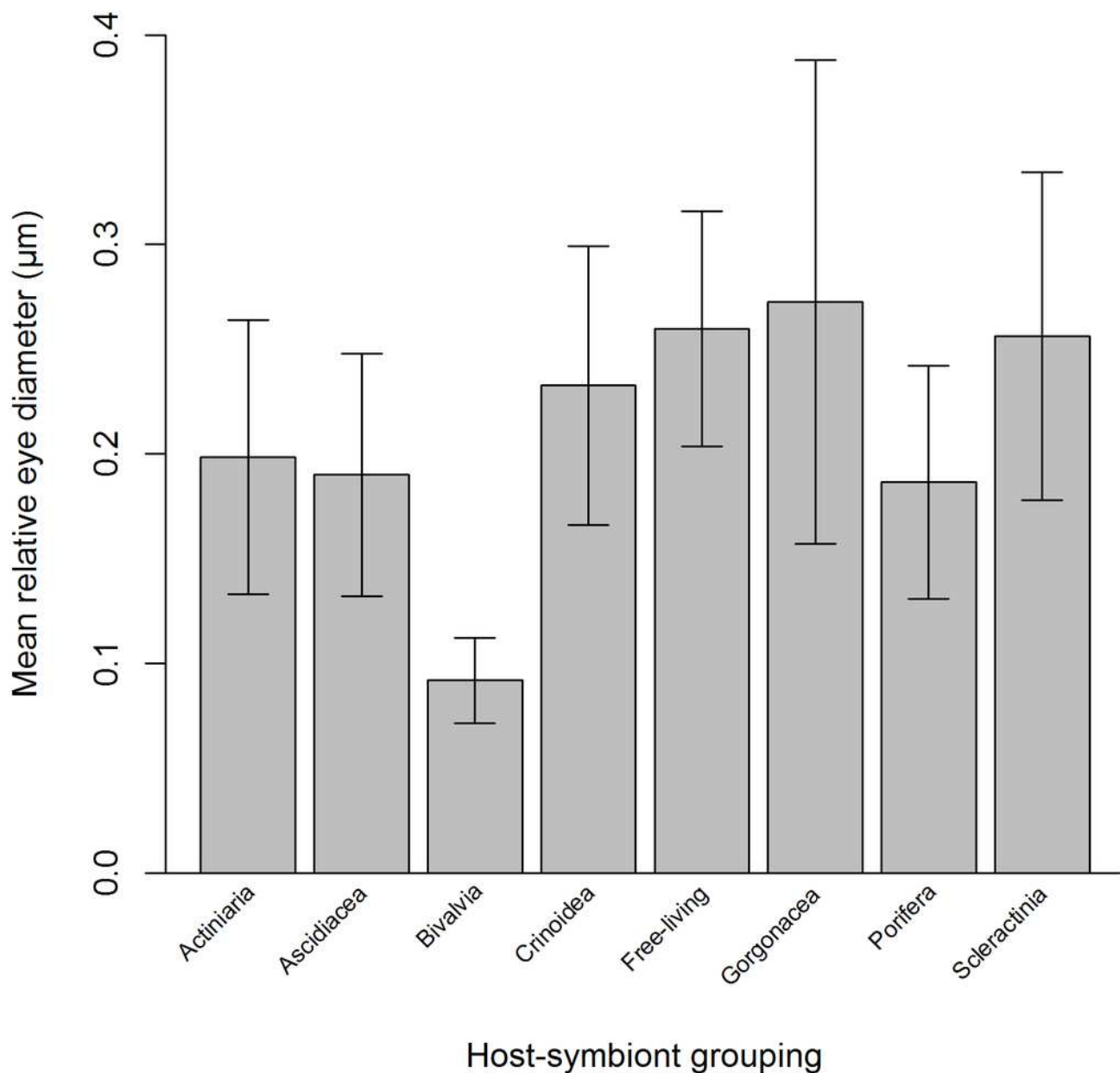
- 370 Duffy, J.E. 1992. Host use patterns and demography in a guild of tropical sponge-dwelling
371 shrimps. - Marine Ecology Progress Series **90**: 127–138.
- 372 Ďuriš, Z., Ateş, A S., Özalp, H B. & Katağan, T.2013. New records of decapod crustaceans
373 (Decapoda: Pontoniinae and Inachidae) associated with sea anemones in Turkish waters. -
374 Mediterranean Marine Science **14**(Special Issue): 49–55.
- 375 Ďuriš, Z., Horká, I., Juračka, P.J., Petrušek, A. & Sandford, F. 2011. These squatters are not
376 innocent: the evidence of parasitism in sponge-inhabiting shrimps. - PLoS ONE **6**(7):
377 e21987.
- 378 Fransen, C.H.J.M. 2002. Taxonomy, phylogeny, historical biogeography, and historical ecology
379 of the genus *Pontonia* Latreille (Crustacea: Decapoda: Caridea: Palaemonidae). -
380 Zoologische Verhandelingen (Leiden) **336**: 1–433.
- 381 Fransen, C.H.J.M. & Reijnen, B.T. 2012. A second discovery of *Lacertopontonia chadi* Marin,
382 2011 (Crustacea: Decapoda: Palaemonidae), with remarks on its systematic position. -
383 Zootaxa **3437**: 43–50.
- 384 Gaten, E., Shelton, P.M.J. & Herring, P.J. 1992. Regional morphological variations in the
385 compound eyes of certain mesopelagic shrimps in relation to their habitat. - Journal of the
386 Marine Biological Association of the United Kingdom **72**: 61–75.
- 387 De Grave, S. 2001. Biogeography of Indo-Pacific Pontoniinae (Crustacea, Decapoda): a PAE
388 analysis. - Journal of Biogeography **28**(10): 1239–1253.
- 389 De Grave, S., Fransen, C.H.J.M. 2015. Let's be pals again: major systematic changes in
390 Palaemonidae (Crustacea: Decapoda). -PeerJ **3**:e1167.
- 391 De Grave, S. & Fransen, C.H.J.M. 2011. Carideorum Catalogus: The recent species of the
392 dendrobranchiate, stenopodidean, procarididean and caridean shrimps (Crustacea:
393 Decapoda). - Zoologische Mededelingen, Leiden **85**: 195–589. Figs 1–59.
- 394 Huebner, L.K. & Chadwick, N.E. 2012. Patterns of cleaning behaviour on coral reef fish by the
395 anemone shrimp *Ancylomenes pedersoni*. - Journal of the Marine Biological Association of
396 the United Kingdom **92**(7): 1557–1562.
- 397 Hultgren, K. & Duffy, J. 2010. Sponge host characteristics shape the community structure of their
398 shrimp associates. - Marine Ecology Progress Series **407**: 1–12.
- 399 Hultgren, K.M. & Duffy, J.E. 2012. Phylogenetic community ecology and the role of social
400 dominance in sponge-dwelling shrimp. - Ecology Letters **15**(7): 704–13.

- 401 Johnson, M.L., Shelton, P.M., Gaten, E. & Herring, P.J. 2000. Relationship of dorsoventral
402 eyeshine distributions to habitat depth and animal size in mesopelagic decapods. - Biological
403 Bulletin **199**(1): 6–13.
- 404 Johnson, M.L., Dobson, N.C. & De Grave, S. 2015. External morphology of eyes and
405 Nebenaugen of caridean decapods – ecological and systematic considerations. - PeerJ.
406 **3**:e1176; DOI 10.7717/peerj.1176
- 407 Johnson, M.L., Shelton, P.M.J. & Gaten, E. 2000. Temporal resolution in the eyes of marine
408 decapods from coastal and deep-sea habitats. - Marine Biology **136**(2): 243–248.
- 409 Kawada, H., Tatsuta, H., Arikawa, K. & Takagi, M. 2006. Comparative study on the relationship
410 between photoperiodic host-seeking behavioral patterns and the eye parameters of
411 mosquitoes. - Journal of Insect Physiology **52**(1): 67–75.
- 412 Kou, Q., Li, X.Z., Chan, T.Y & Chu, K.H. 2014. Divergent evolutionary pathways and host shifts
413 among the commensal pontoniine shrimps: a preliminary analysis based on selected Indo-
414 Pacific species. - Organisms Diversity & Evolution **15**: 369–377.
- 415 Limbaugh, C., Pederson, H. & Chace, F.A. 1961. Shrimps that clean fishes. - Bulletin of Marine
416 Science **11**(2): 237–257.
- 417 Marin, I. 2009a. A review of the pontoniine shrimp genus *Rapipontonia* Marin, 2007 (Decapoda:
418 Caridea: Palaemonidae), with the description of a new species from the Indo-West Pacific. -
419 Zootaxa **2289**: 1–17.
- 420 Marin, I. 2009b. Crinoid-associated shrimps of the genus *Laomenes* A.H. Clark, 1919 (Caridea:
421 Palaemonidae: Pontoniinae): new species and probable diversity. - Zootaxa **1971**: 1–49.
- 422 Marin, I. & Anker, A. 2008. A new species of *Pontonia* Latreille, 1829 (Crustacea, Decapoda,
423 Palaemonidae) associated with sea squirts (Tunicata, Ascidiacea) from the Pacific coast of
424 Panama. - Zoosystema **30**(2): 501–515.
- 425 Patton, W.K. 1994. Distribution and ecology of animals associated with branching corals
426 (*Acropora* spp.) from the Great Barrier Reef, Australia. - Bulletin of Marine Science **55**(1):
427 193–211.
- 428 R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for
429 Statistical Computing. - Vienna, Austria, ISBN 3-900051-07-0. Available at: [http://www.r-](http://www.r-project.org)
430 [project.org](http://www.r-project.org).
- 431 Snyder, A.W. 1979. Physics of vision in compound eyes. Pp 225–313 in: H. Autrum, (eds).
432 Comparative Physiology and Evolution of Vision in Invertebrates A: Invertebrate
433 photoreceptors. - Springer-Verlag, Berlin.

- 434 Stavenga, D.G. 2003. Angular and spectral sensitivity of fly photoreceptors. II. Dependence on
435 facet lens F-number and rhabdomere type in *Drosophila*. - Journal of Comparative
436 Physiology A, **189**(3): 189–202.
- 437 Stavenga, D.G. & Hardie, R.C. 1989. Facets of vision. - Springer-Verlag, London.
- 438 Stella, J.S. Pratchett, M.S., Hutchings, A.P. & Jones, G.P. 2011. Coral-associated invertebrates:
439 diversity, ecological importance and vulnerability to disturbance. - Oceanography and
440 Marine Biology: An annual review **49**: 43–104.
- 441 Zuur, A.F., Ieno, E.N. & Elphick, C.S. 2010. A protocol for data exploration to avoid common
442 statistical problems. - Methods in Ecology and Evolution **1**(1): 3–14.

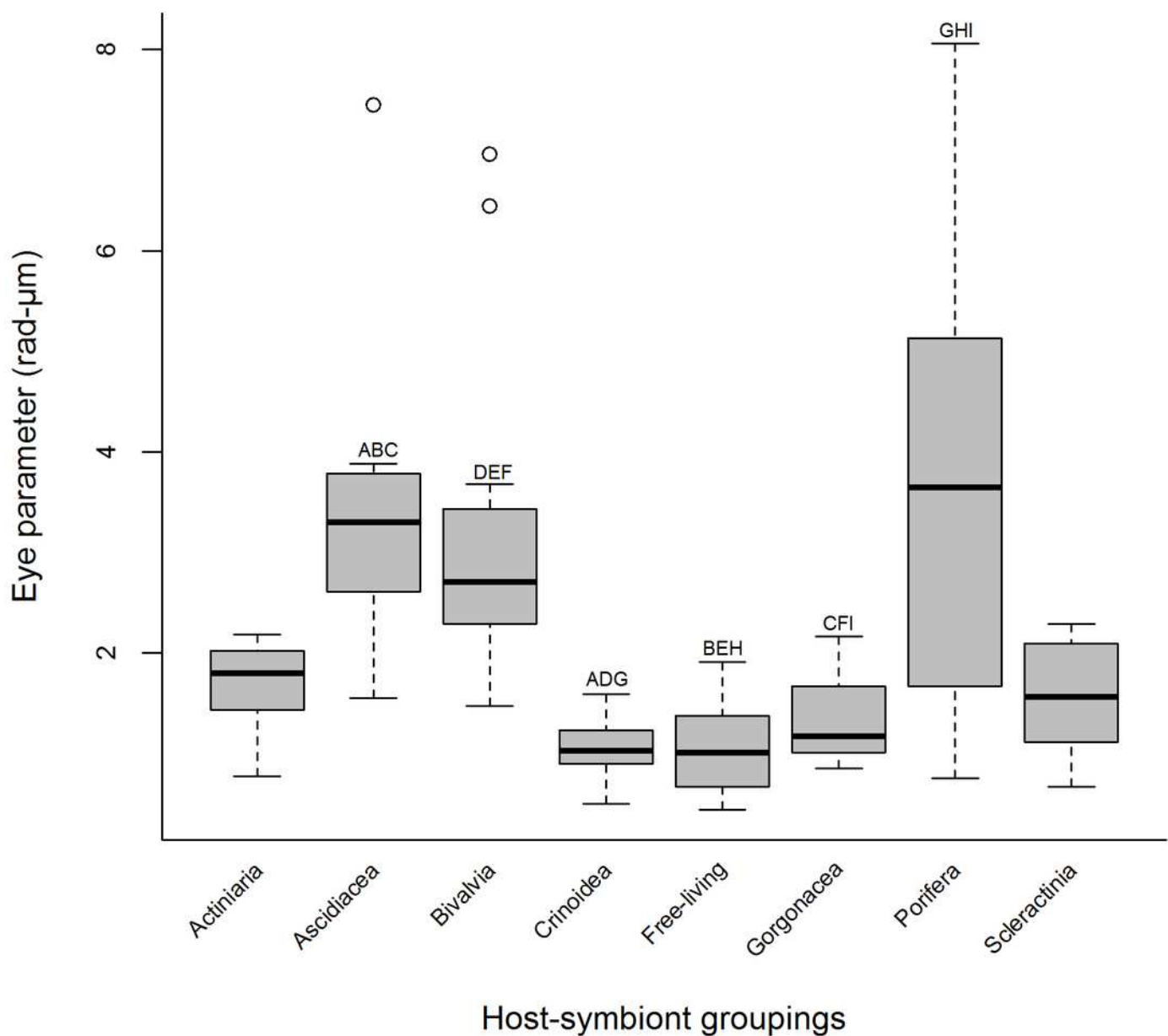
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Figure 1. Mean relative eye diameter (standardised by post-orbital carapace length) for 83 species of Pontoniinae associated 8 host-symbiont groupings.



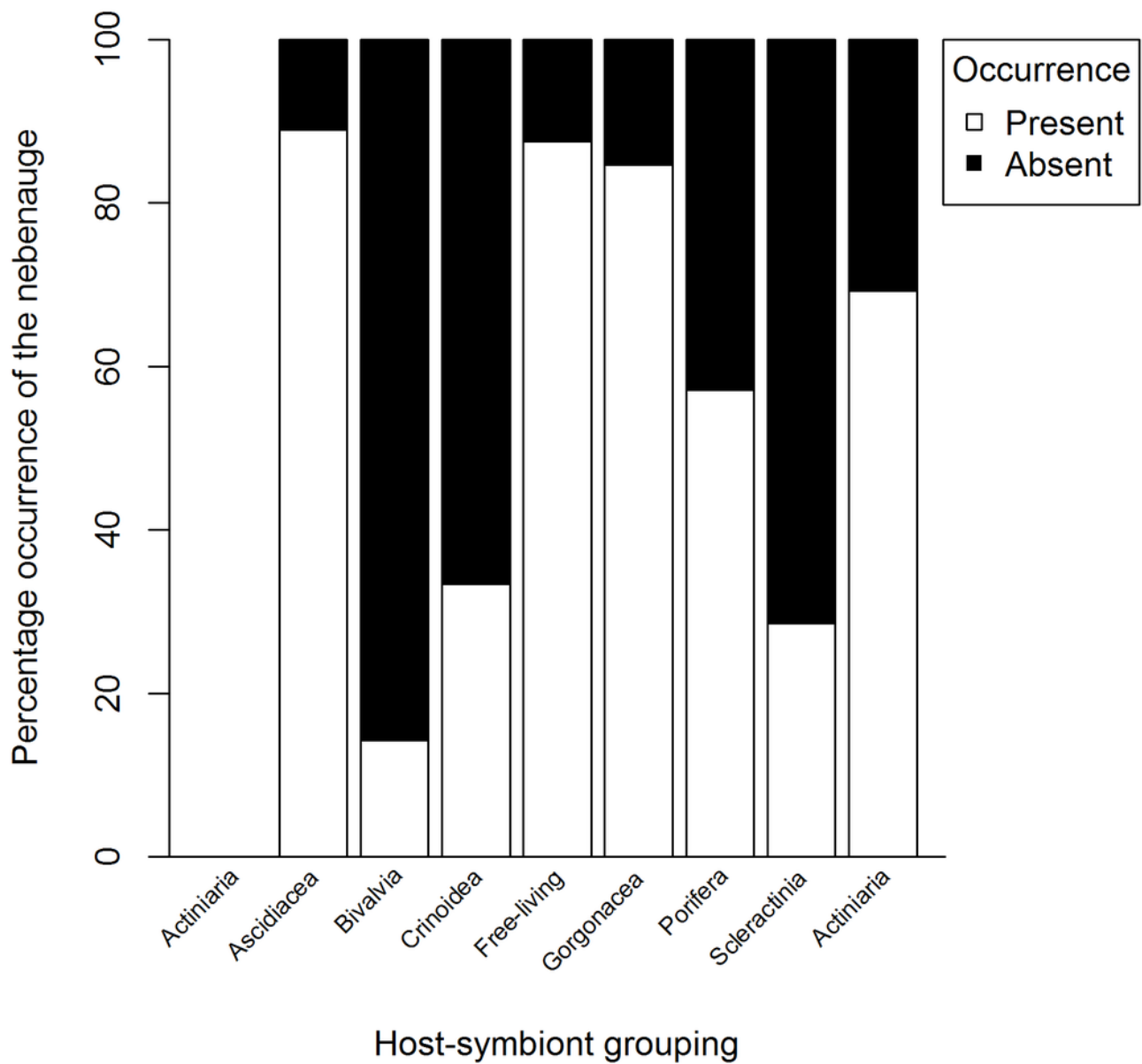
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Figure 2. Median eye parameter for 83 species of Pontoniinae from 8 host-symbiont groupings. Significant differences are represented by hosts possessing the same letter A-I (Tukey HSD $P < 0.05$).



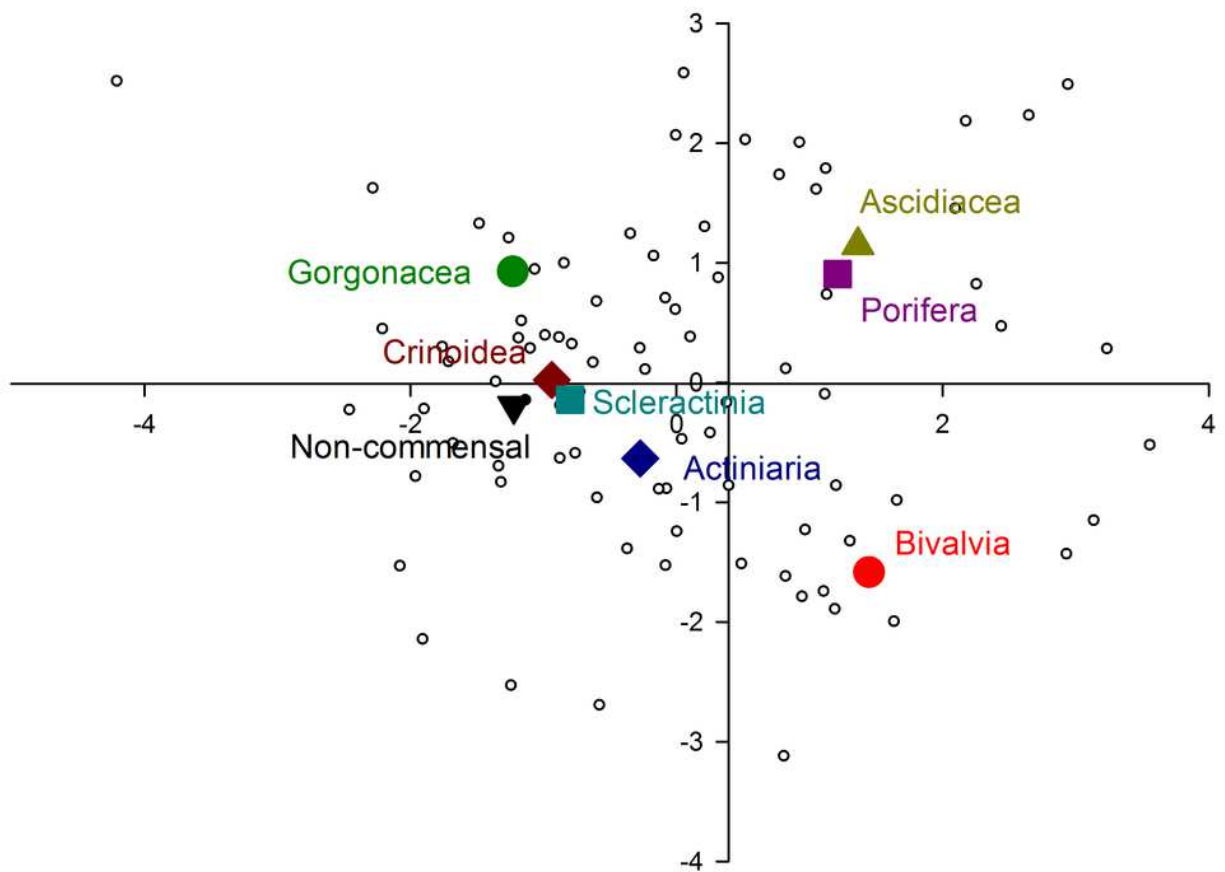
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Figure 3. Percentage occurrence of the nebenauge for 83 species of Pontoniinae from 8 host-symbiont groupings.



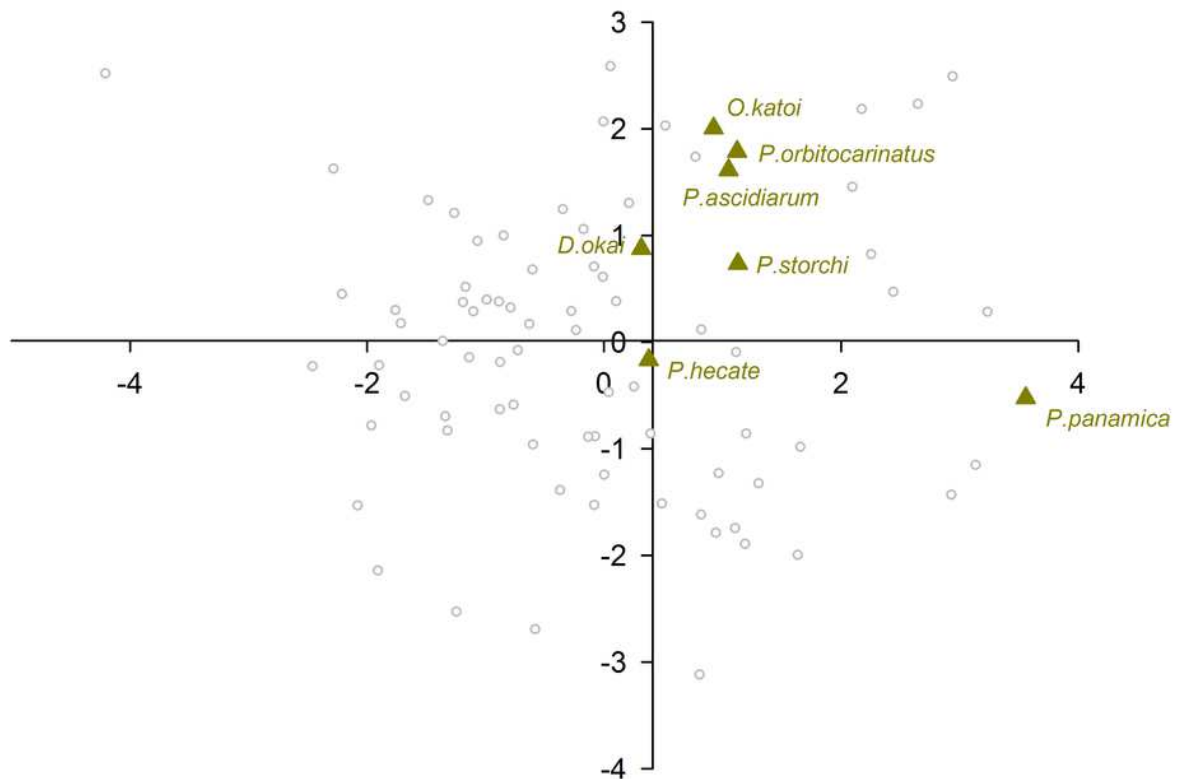
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Figure 4. Morphological variation demonstrated by the DFA scores (first and second root only) of all 83 species of pontonine shrimps (grey circles) displaying the positioning of the centroids for each of the 8 hosts-symbionts groups.



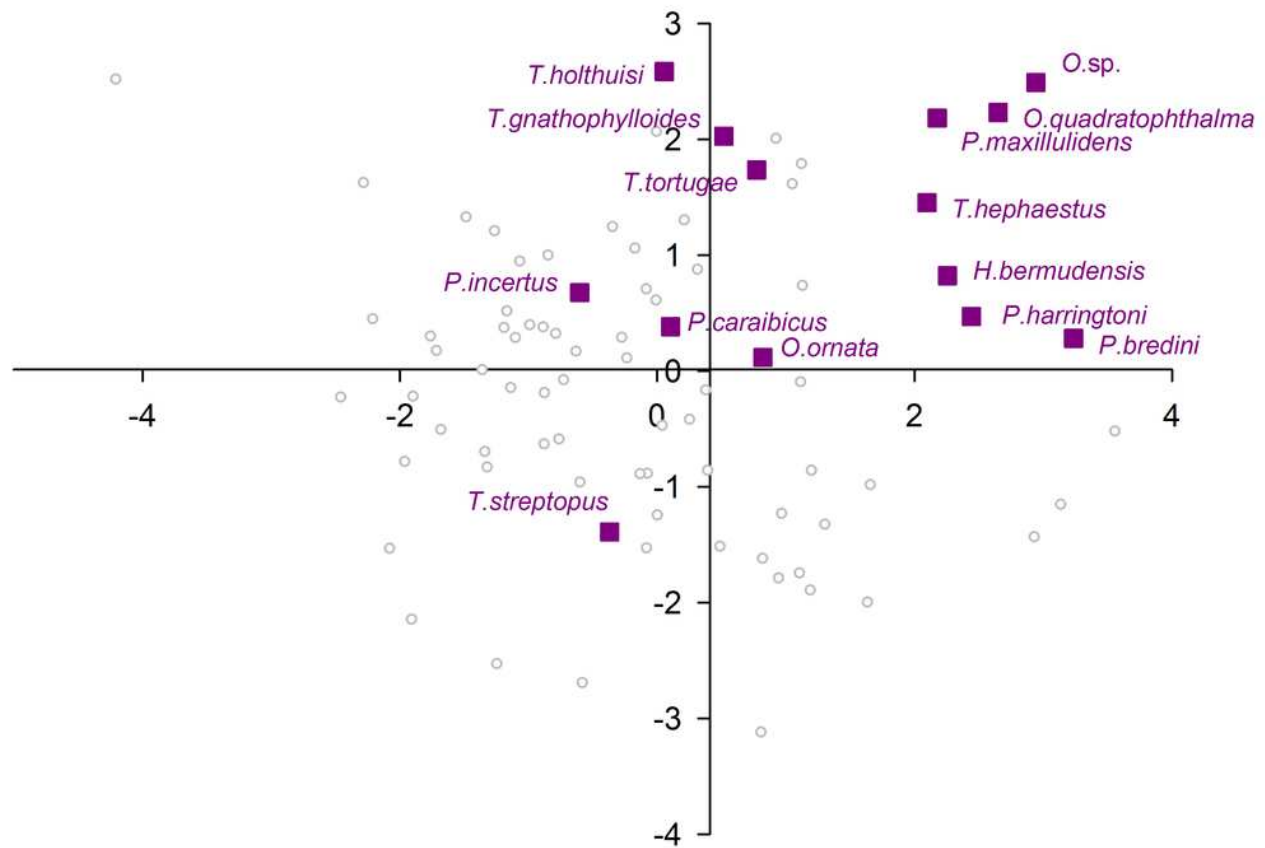
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Figure 5. Morphological variation demonstrated by the DFA scores (first and second root only) of Ascidiacea associates.



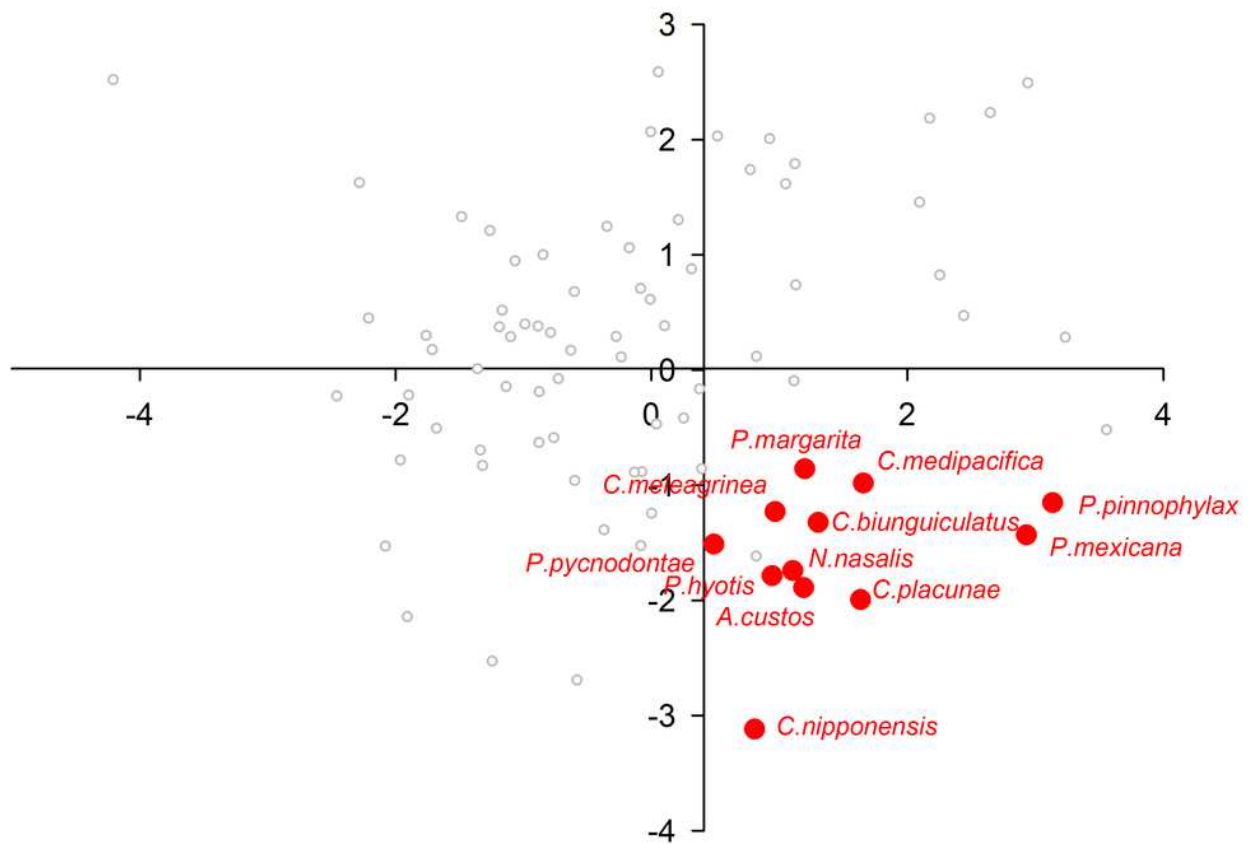
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Figure 6. Morphological variation demonstrated by the DFA scores (first and second root only) of Porifera associates.



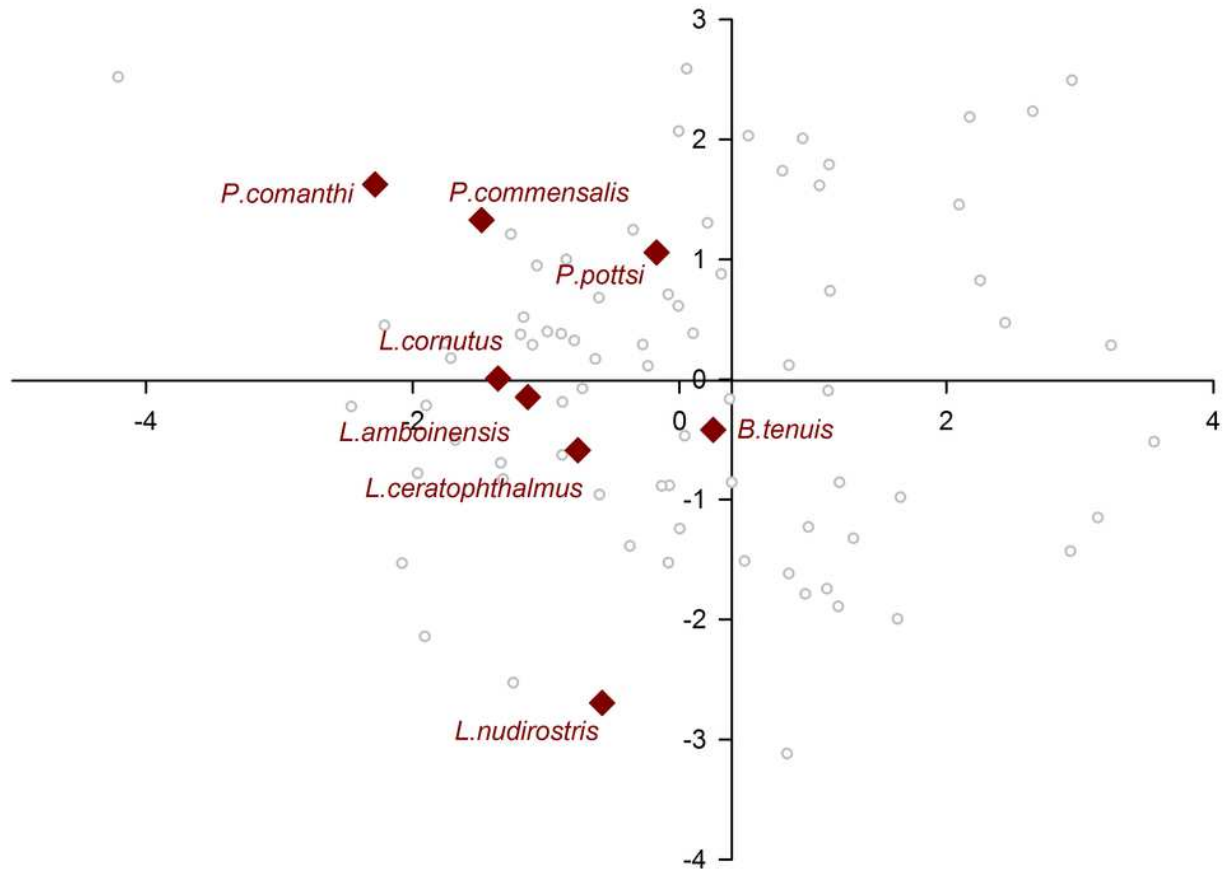
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Figure 7. Morphological variation demonstrated by the DFA scores (first and second root only) of Bivalvia associates.



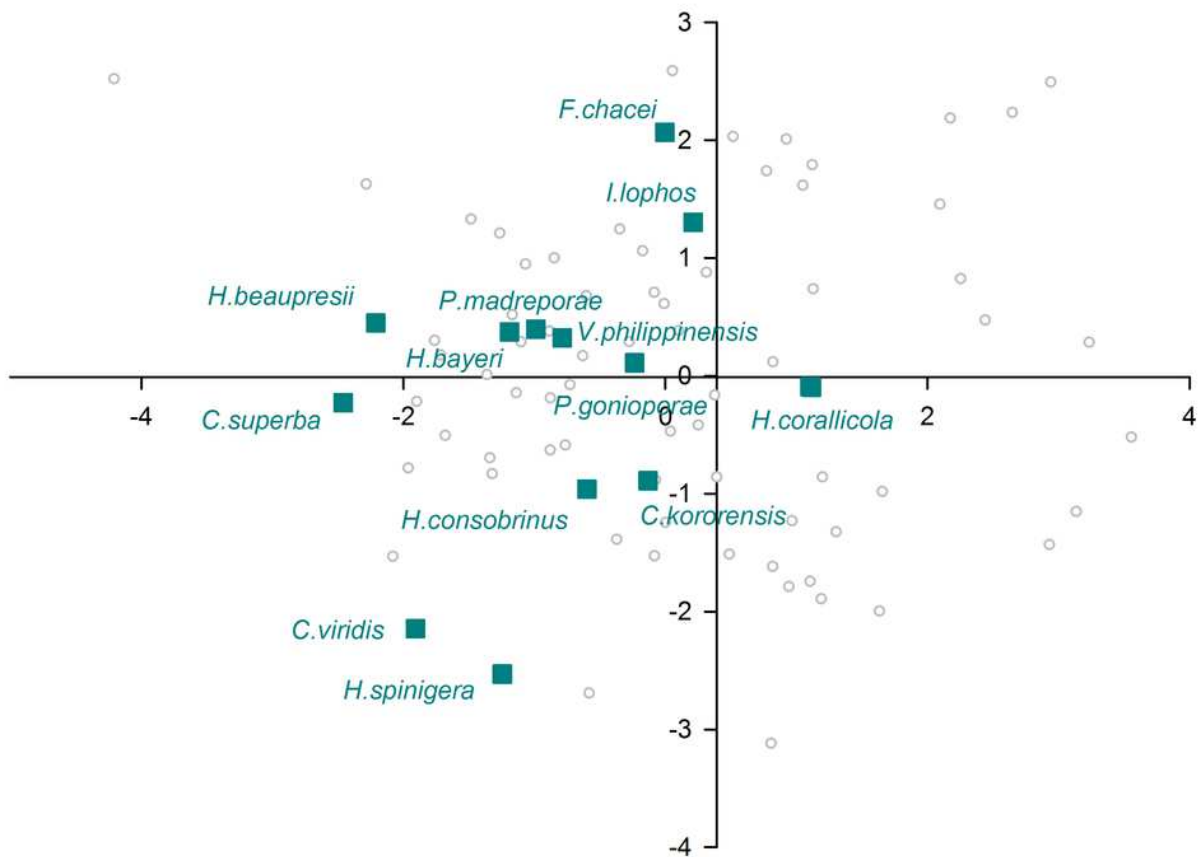
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Figure 8. Morphological variation demonstrated by the DFA scores (first and second root only) of Crinoidea associates.



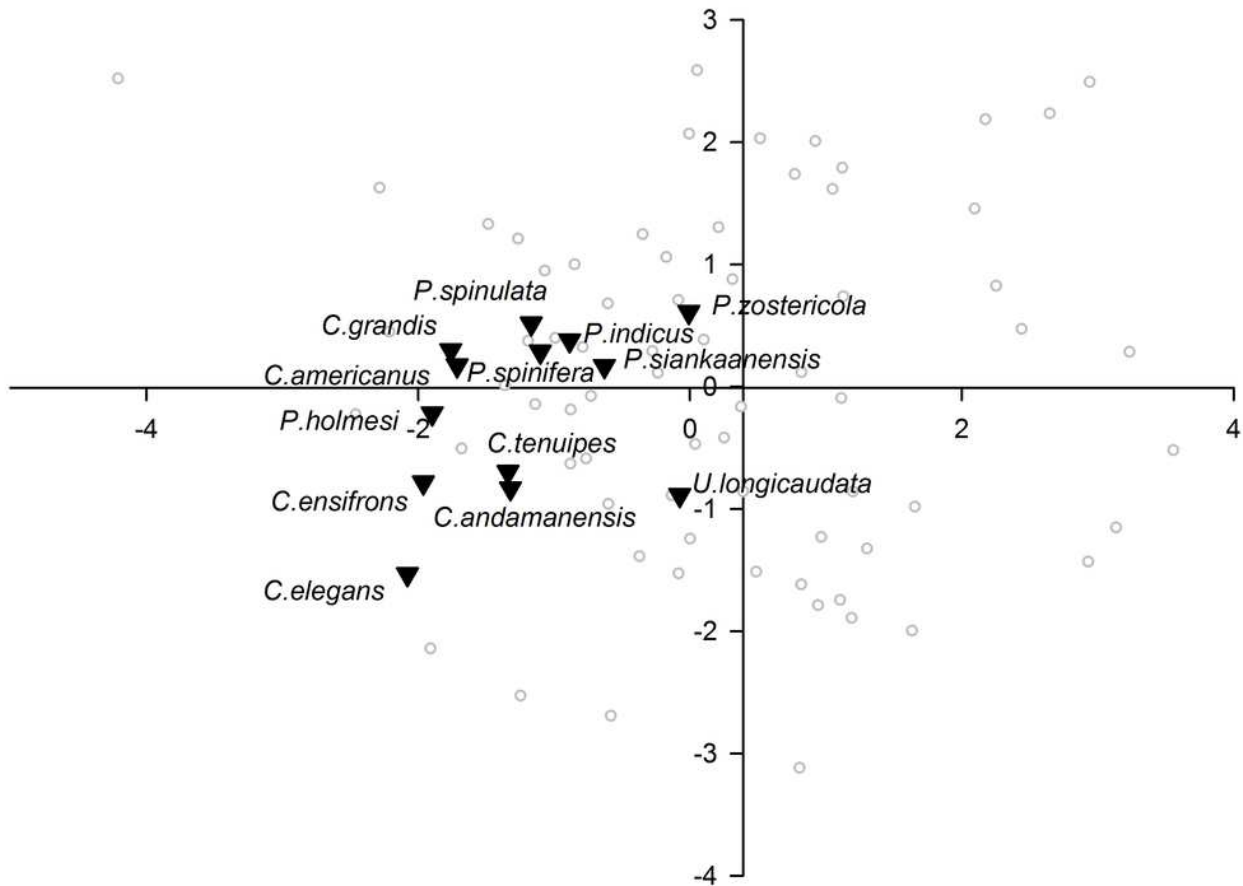
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Figure 9. Morphological variation demonstrated by the DFA scores (first and second root only) of Scleractinia associates.



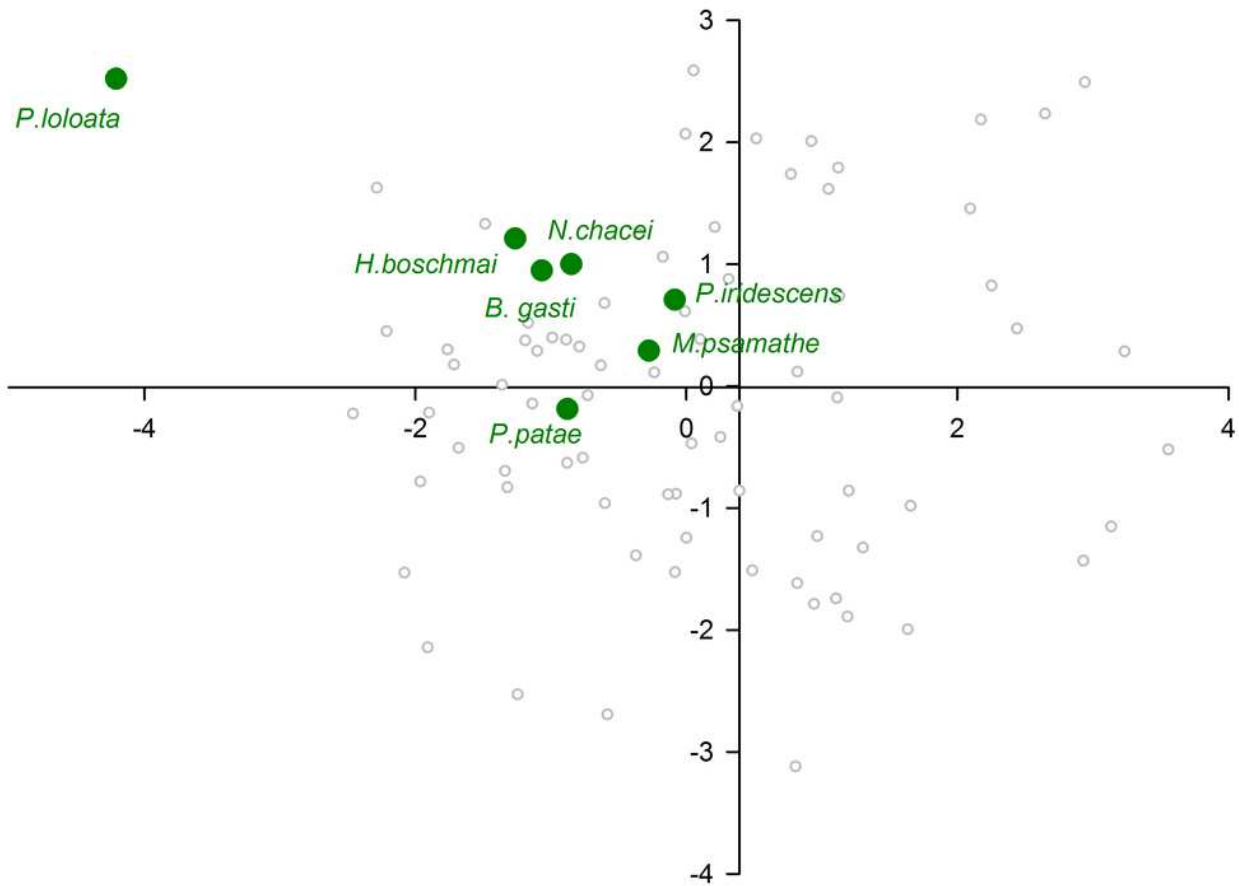
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Figure 10. Morphological variation demonstrated by the DFA scores (first and second root only) of non-commensal species.



11

Figure 11. Morphological variation demonstrated by the DFA scores (first and second root only) of Gorgonacea associates.



12

Figure 12. Morphological variation demonstrated by the DFA scores (first and second root only) of Actiniaria associates.

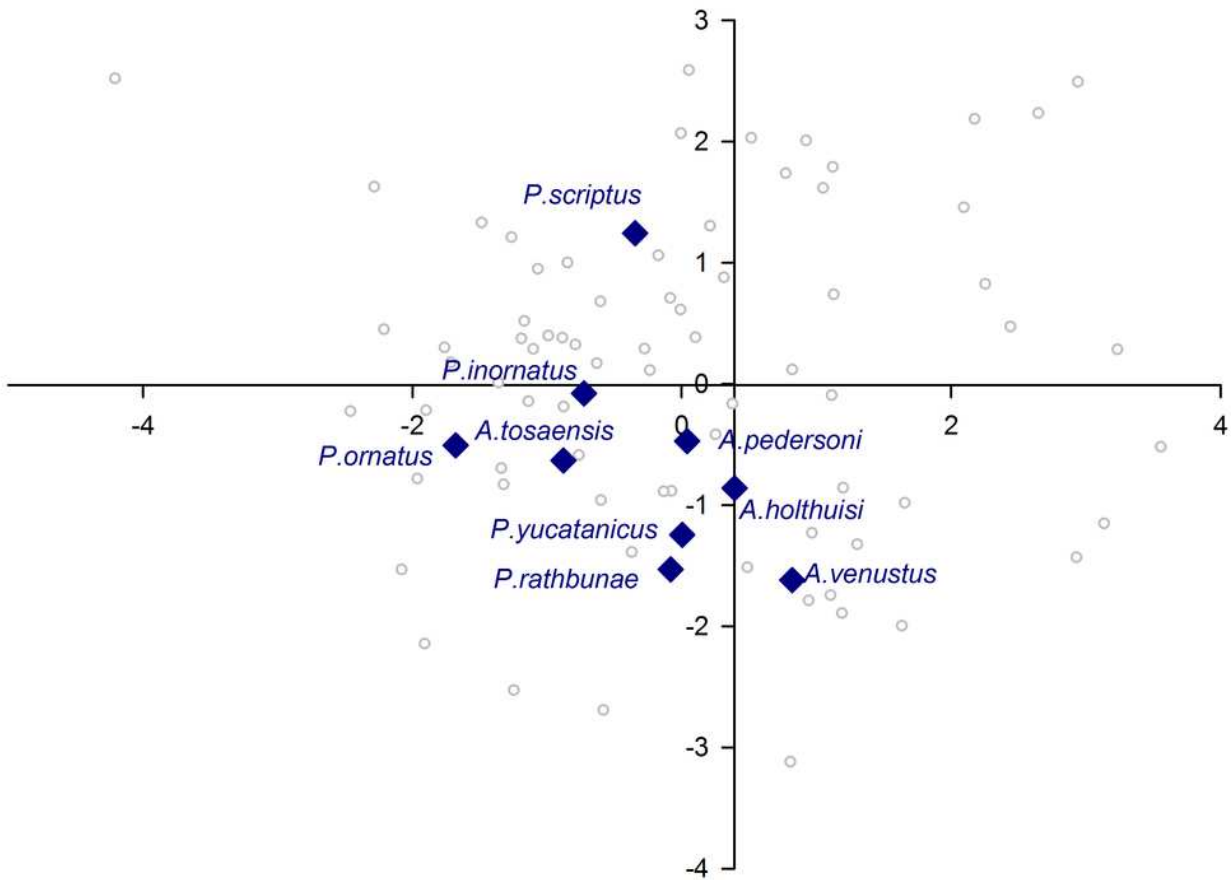


Table 1 (on next page)

Table 1. Summary statistics for DFA analysis.

1 Table 1. Summary statistics for DFA analysis

2

| | Eigenvalue | % of variance | Cumulative % | Canonical correlation | Wilks's λ | <i>P</i> value |
|--------|------------|------------------|-----------------|--------------------------|----------------------|-------------------|
| Root 1 | 1.436 | 59.1 | 59.1 | 0.768 | 0.194 | <0.005 |
| Root 2 | 0.864 | 35.5 | 94.6 | 0.681 | 0.473 | <0.005 |
| Root 3 | 0.090 | 3.7 | 98.4 | 0.288 | 0.882 | 0.482 |
| Root 4 | 0.040 | 1.6 | 100 | 0.196 | 0.962 | 0.561 |

3

Table 2 (on next page)

Table 2. Structure matrix of discriminant loadings, with the largest absolute correlation between each variable and any discriminant function indicated by *. All variables were entered simultaneously.

1 Table 2. Structure matrix of discriminant loadings, with the largest absolute correlation between
2 each variable and any discriminant function indicated by *. All variables were entered
3 simultaneously.

4

| | Function 1 | Function 2 |
|----------|------------|------------|
| ArcsinFD | 0.808* | 0.482 |
| EP | 0.718* | 0.166 |
| ArcsinED | -0.657* | 0.481 |
| ES-DBES | -0.158 | -0.695* |

5

Table 3 (on next page)

Table 3. DFA Classification matrix, showing number of species correctly and incorrectly classified into a priori defined groups, expressed as a percentage of within group species numbers.

Table 3. DFA Classification matrix, showing number of species correctly and incorrectly classified into a priori defined groups, expressed as a percentage of within group species numbers.

| | | DFA classification | | | | | | | |
|---|---------------|--------------------|------------|----------|-----------|---------------|------------|----------|--------------|
| | | Actiniaria | Ascidiacea | Bivalvia | Crinoidea | Non-commensal | Gorgonacea | Porifera | Scleractinia |
| A p r i o r i g r o u p s | Actiniaria | 22.2 | - | 11.1 | 11.1 | 22.2 | - | - | 33.3 |
| | Ascidiacea | 14.3 | - | 14.3 | - | - | - | 71.4 | - |
| | Bivalvia | - | - | 100.0 | - | - | - | - | - |
| | Crinoidea | 25.0 | - | - | 12.5 | 12.5 | 37.5 | - | 12.5 |
| | Non-commensal | 7.7 | - | - | 15.4 | 61.5 | - | - | 15.4 |
| | Gorgonacea | - | - | - | 28.6 | 14.3 | 42.9 | - | 14.3 |
| | Porifera | 7.1 | - | - | 14.3 | - | - | 78.6 | - |
| | Scleractinia | 15.4 | - | - | 7.7 | 15.4 | - | 23.1 | 38.5 |