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1 **A method for selecting health index metrics in the absence of independent measures**
2 **of ecological condition**

3

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26 **Abstract**

27 We describe a novel, weight of evidence-based approach for selecting fish community
28 metrics to assess estuarine health, and its application in selecting metrics for a multi-metric
29 health index for the Swan Estuary, Western Australia. In the absence of reliable,
30 independent measures of estuarine condition against which to test the sensitivity of
31 candidate metrics, objective, multivariate statistical analyses and multi-model inference
32 were employed to select metric subsets likely to be most sensitive to inter-annual changes
33 in the health of this ecosystem. Novel pre-treatment techniques were first applied to down-
34 weight the influence of highly erratic metrics and to minimise the effects of seasonal and
35 spatial differences in sampling upon metric variability. A weight of evidence approach was
36 then adopted to select those metrics which responded most consistently across multiple
37 analyses of nearshore and offshore fish abundance data sets collected between 1976 and
38 2009. Sets of 11 and seven metrics were selected for assessing the health of the nearshore
39 and offshore waters of the Swan Estuary, respectively. Selected metrics represented
40 species composition and diversity, trophic structure, life history and habitat functions and,
41 in the case of the nearshore index, a potential sentinel species. These metric sets are
42 currently being used to construct a multi-metric health index for the Swan Estuary, which
43 is the first such tool to be developed for assessing the health of estuaries in Australia. More
44 broadly, while the methodology has in the present case been applied to the fish fauna of
45 the Swan Estuary, it is generally applicable to any ecosystem and type of biotic
46 community from which an ecosystem health index might be sensibly derived.

47

48 **Keywords:** ecological integrity, ecosystem health, fish community, guild, metric selection,
49 sensitivity

50

51 **1. Introduction**

52 Multi-metric biotic indices integrate information from a suite of characteristics
53 (metrics) of the biological communities upon which they are based to provide an
54 assessment of the ecological integrity of ecosystems (Karr, 1981; Gibson et al., 2000).
55 These indices typically comprise metrics that measure the species composition, diversity
56 and trophic, habitat and/or life history structure of the assemblage such that, in
57 combination, they reflect the structure and function of the ecosystem of interest. Such
58 indices are now a key component of national estuarine monitoring programs in the United
59 States, South Africa and Europe (Deegan et al., 1997; Bilkovic et al., 2005; Harrison and
60 Whitfield, 2006; Uriarte and Borja, 2009) although, to date, their application to Australian
61 estuaries has been limited (Borja et al., 2008).

62 Typically, independent measures of ecosystem condition are used to test
63 hypotheses of metric responses to changes in physical habitat quality (Deegan et al., 1997),
64 water quality (Hughes et al., 1998) or anthropogenic degradation (Breine et al., 2007), and
65 those metrics which are most sensitive to these types of environmental degradation are
66 then selected as those which best reflect ecosystem health, for inclusion in a multi-metric
67 index. However, in several cases, such independent measures of ecosystem condition are
68 not readily available, thereby limiting any of the currently-known quantitative methods for
69 selecting the most useful suite of metrics. The only alternative in such cases is to employ
70 expert judgement, which not only suffers from the influence of subjectivity, but provides
71 no sound evidence that the suite of metrics selected is the most useful.

72 We outline a novel, quantitative and broadly applicable approach for selecting the
73 most responsive subset of metrics for constructing a multimetric biotic index. This
74 approach, which can be applied to any appropriate biota in any ecosystem, employs a
75 combination of multivariate statistical analyses to assess metric sensitivity and

76 redundancy, thereby allowing the most useful and parsimonious subset of metrics to be
77 selected for subsequent incorporation into a multi-metric index of ecosystem health.

78 To outline this approach and demonstrate its characteristics, we sought to select
79 appropriate fish community metrics from which to construct a multi-metric, biotic health
80 index for the permanently-open Swan Estuary, located on the lower west coast of Western
81 Australia (WA) (32.055°S, 115.735°E; Fig. 1). Due to the lack of established national or,
82 until recently, State strategies for monitoring and assessing estuarine health in Australia,
83 existing schemes, which have been based largely on water quality or floral communities,
84 have generally been limited in scope, poorly developed and/or inconsistently applied and
85 tested (Deeley and Paling, 1998; Borja et al., 2008; Hirst, 2008). This is particularly so in
86 WA, which suffers from a lack of existing ecological indicators or independent measures
87 of habitat quality for systems including the Swan Estuary, against which the sensitivity of
88 candidate fish metrics might be assessed.

89

90 **2. Methods**

91 *2.1. Collation of data sets*

92 Given a lack of knowledge of the magnitude and/or direction of change in the
93 health of the Swan Estuary (or any such ecosystem) over time, the approach to metric
94 selection which we describe rests on the assumption that the ecological condition of the
95 estuary has simply varied over time, in an unquantified and non-directional manner, in
96 response to changes in the suite of stressors acting upon it. Given this assumption, the
97 approach to metric selection described here focused on selecting that subset of candidate
98 metrics that most consistently exhibited inter-annual changes at the ecosystem level over
99 periods spanning 33 years, and thus which are likely to be most sensitive to longer-term
100 changes in ecosystem condition. This approach was applied across multiple sets of fish

101 species abundance data collected during each season in particular regions of the Swan
102 Estuary, both historically (1976-2007) and during the current study (2007-09; Table 1; Fig.
103 1). As marked seasonal and regional differences in fish community composition have been
104 documented for the Swan Estuary (Loneragan et al., 1989; Loneragan and Potter, 1990;
105 Kanandjembo et al., 2001; Hoeksema and Potter, 2006), which would increase metric
106 variability and potentially obscure their responses to inter-annual changes in ecosystem
107 condition, data sets selected for inclusion in these analyses were restricted to those that
108 were collected at comparable locations and times of year.

109 Details of the sampling regimes and methods used historically to collect fish
110 community data throughout the Swan Estuary can be found in the published accounts of
111 those studies, listed in Table 1. Sampling during the current study was performed
112 throughout the estuary during the middle month of each season from winter 2007 to
113 autumn 2009. Both 21.5 and 41.5 m-long seine nets were employed in the nearshore
114 waters (<2 m deep) and multi-mesh gill nets were used in the offshore waters (>2 m deep);
115 the dimensions and mesh sizes of these nets being consistent with those of similar nets
116 employed historically (Table 1). Fish collected were immediately placed in an ice slurry
117 and taken to the laboratory for processing. All fish were identified to species and the total
118 number of individuals belonging to each species in each sample was recorded. The total
119 length of each fish was measured to the nearest 1 mm, except when a large number of
120 individuals of any one species was encountered in a sample, in which case the lengths of a
121 representative subsample of 50 individuals were measured.

122

123 *2.2. Allocation of fish to ecological guilds*

124 All fish species encountered in the Swan Estuary during studies of this system were
125 first allocated to functional ecological guilds (Potter and Hyndes, 1999; Elliott et al., 2007;

126 Franco et al., 2008) to enable the calculation of various candidate metrics (see Appendix A
127 for a full list of these guilds). Three categories of guilds were employed, namely (i)
128 ‘Habitat’, which reflects the relative size and preferred position within the water column of
129 each species, (ii) ‘Estuarine Use’, which reflects the proportion of their life cycle that each
130 species spends in the estuary and their main activities in that environment, i.e. life history,
131 and (iii) ‘Feeding Mode’, which reflects the diet of the adults of each species (Noble et al.,
132 2007). Guild allocation was undertaken on the basis of information contained within the
133 Codes for Australian Aquatic Biota (Rees et al., 1999), published literature and FishBase
134 (Froese and Pauly, 2007).

135

136 2.3. Candidate fish metrics

137 A list of candidate fish metrics was compiled from an extensive review of existing
138 fish-based indices for estuaries throughout the world and using expert knowledge of the
139 fish fauna of the Swan Estuary. These candidate metrics represented a range of fish
140 community characteristics, including measures of species composition and diversity,
141 trophic structure, life history and habitat functions, and also included a potential ‘sentinel’
142 species (Noble et al., 2007), the Blue-spot, or Swan River Goby, *Pseudogobius olorum*
143 (Table 2). This species has various adaptations that make it well-suited to survival in
144 degraded environments, including its tolerance of hypoxic conditions (H. Gill, Murdoch
145 University, personal communication), which reflects its ability to use atmospheric oxygen
146 via aquatic surface respiration (Gee and Gee, 1991), its ‘preference’ for silty substrates
147 (Gill and Potter, 1993) and its omnivorous feeding mode. Where appropriate, two potential
148 variants of each fish metric were calculated and assessed, namely ‘number of taxa’ and
149 ‘proportion of total individuals’, as recommended by Noble et al. (2007).

150 Prior to selecting those fish metrics that exhibited the most consistent inter-annual
151 differences and thus could be considered to be the most sensitive to temporal shifts in
152 ecosystem health, several candidate metrics were eliminated from further consideration on
153 the basis of their ambiguous nature (total fish density), high correlation with other metrics
154 (various trophic structure metrics, including the contributions of piscivores, carnivores,
155 omnivores and opportunistic species) or a lack of information (Pielou's evenness index
156 [which is undefined for zero catches], the contribution of introduced species and its
157 complement, the contribution of native species). Elimination of these metrics generated a
158 refined list of candidate metrics to be tested for inclusion in the index of estuarine health
159 (Table 3).

160 Data derived from samples collected during all studies using each of the four
161 sampling methods listed in Table 1 (i.e. the 21.5, 41.5 and 102-133 m seine nets in the
162 nearshore waters and the gill net in the offshore waters) were analysed separately to
163 overcome the effects of gear-induced biases. Values for each of the candidate metrics in
164 the refined list (Table 3) were calculated for each replicate sample in each data set, and the
165 resultant data were then subjected to the following statistical analyses in the PRIMER v6
166 multivariate statistics package (Clarke and Gorley, 2006) with the PERMANOVA+ for
167 PRIMER add-on module (Anderson et al., 2008), to identify that subset of metrics that
168 most consistently exhibited inter-annual differences between 1976 and 2009 in both the
169 nearshore and offshore waters of the Swan Estuary.

170

171 *2.4. Data pre-treatment*

172 The 21.5, 41.5 and 102-133 m seine net metric data sets (hereafter '21 m data set',
173 '41 m data set' and '102-133 m data set', respectively) were each used, in combination, to
174 select the most informative subset of metrics for incorporation into an index of health for

175 the nearshore waters of the Swan Estuary, and the gill net data set was used to select
176 metrics for incorporation into a similar index for the offshore waters of the Swan Estuary.
177 Prior to analysis, each metric in each data set was transformed, where necessary, to
178 stabilise its variance across different region*season*year combinations, so that standard
179 general linear models could be fitted to the data. The most appropriate transformation in
180 each case was determined by ascertaining the slope of the relationship between $\log_e(\text{mean})$
181 and $\log_e(\text{SD})$ for the various groups of replicate samples, i.e. each of the above
182 combinations (Clarke and Warwick, 2001). Depending on the extent of this slope,
183 transformations selected from the set of none, $x^{0.5}$, $x^{0.25}$, $\log_e(c_1 + x)$ were applied to either
184 the x value or its complement, $c_2 - x$, where c_1 is typically 0.01 and c_2 is typically 1 for
185 proportions. For each of these data sets, the draftsmans plot routine was used to ascertain
186 the degree to which each pair of metrics was highly correlated (i.e. Pearson's correlation
187 coefficient [$r \geq 0.95$]), and thus the extent of redundancy among metrics. The metrics *Prop*
188 *trop gen*, *No detr*, *No est res* and *Prop est res* (see Table 3 for metric codes) were found to
189 be highly correlated with other metrics in each nearshore and offshore data set, and were
190 thus eliminated from further analyses. In addition, the metrics *Prop P. olorum* and
191 *Tot no P. olorum* were also eliminated from the latter data set, as the small goby species
192 *Pseudogobius olorum* is not captured by the gill nets employed to sample offshore waters.

193 As the values of the fish metrics for each data set exhibited marked differences in
194 their relative variability within groups of replicate samples, even after transformation, each
195 was then divided by its average standard deviation (calculated as the mean of the standard
196 deviations for each group of region*season*year replicates) to weight it by its inherent
197 variability. This novel pre-treatment step thus relatively down-weighted the influence of
198 highly erratic, 'noisy' metrics whilst relatively up-weighting the influence of those metrics
199 with comparatively consistent values across replicate samples.

200 In order to focus on the inter-annual differences in fish metric composition in each
201 of the data sets, the confounding effects that differences among regions and seasons and
202 their interactions are known to have on the composition of fish communities in the Swan
203 Estuary were removed in the standard way for a general linear model by moving all
204 samples to a common centroid in Euclidean space. This was achieved for each pre-treated
205 metric in each data set by initially calculating the mean of all samples (across all years) in
206 each region*season group, then subtracting the relevant region*season mean from each
207 sample value. The resultant data for each metric thus comprised the main inter-annual
208 effects and residual differences under the reduced model (but note, also included the
209 effects of any interactions between years and regions or seasons).

210

211 *2.5. Model matrix construction*

212 For each of the data sets, a Euclidean distance matrix containing all pairs of
213 sampling years between 1976 and 2009 was then constructed from the reduced metric
214 residuals. This matrix was also used to create a ‘model resemblance matrix’, whereby
215 samples from the same year had a distance of 0 and samples from different years had a
216 distance of 1. This model resemblance matrix, in conjunction with the data matrix of
217 reduced metric residuals, was subsequently used in the following two approaches to
218 identify those metrics which exhibited the most consistent inter-annual differences.

219

220 *2.6. Modelling and weight of evidence*

221 Firstly, distance-based linear modelling (DISTLM; McArdle and Anderson, 2001)
222 was used in a novel way to determine the subset of ‘predictor’ variables (fish metrics)
223 which best modelled the ‘response’ data cloud (the 0-1 model matrix), and thus whose
224 values were relatively constant within any year, yet differed consistently between years.

225 The proportion of explained variation (r^2) was calculated for each model (i.e. combination
226 of predictor variables), although the value of this selection criterion always increases with
227 the number of predictor variables and thus does not provide a good basis for the selection
228 of parsimonious metric sets. Therefore, the selection criterion employed in this analysis
229 was a modified version of the information criterion (AIC) described by Akaike (1973),
230 namely AIC_c , which was developed for application in situations like that of the current
231 study, where the number of samples (n) relative to predictor variables (q) is small, i.e. n / q
232 < 40 (Burnham and Anderson, 2002). The selection procedure used was the ‘Best’
233 procedure, which calculates AIC_c for all possible models and identifies that with the lowest
234 AIC_c value ($AIC_{c(\min)}$) as the estimated ‘best’ of the candidate models.

235 It is important to note that, according to information theory, competing models
236 with AIC_c values within 2 units of $AIC_{c(\min)}$ are also substantially supported by the
237 evidence and are useful in estimating the uncertainty associated with any likely ‘best’
238 model for the data set (Burnham and Anderson, 2002). Thus, by analogy, we propose that
239 AIC_c differences (Δ_i) can be calculated for each competing model (i) according to the
240 equation $\Delta_i = AIC_{c(i)} - AIC_{c(\min)}$, to allow comparison and ranking of those models. For
241 each of the data sets, the subset of models with $\Delta_i \leq 2$ were identified and the relative log-
242 likelihoods of each of these models were calculated as being equal to $\exp(-0.5 * \Delta_i)$. To
243 better interpret the strength of evidence supporting each of the models in the subset, these
244 log-likelihoods were then normalized to produce a set of positive Akaike weights (w_i)
245 summing to 1 (Burnham and Anderson, 2002). Finally, evidence ratios (w_1 / w_i , where
246 model 1 is the estimated ‘best’ in the set) were calculated to examine the relative
247 likelihood of each model compared to the estimated ‘best’ model. Note that, according to
248 Burnham and Anderson’s (2002) convention for calculating evidence ratios, a ratio of 2.7
249 indicates, for example, that model i is 2.7 times less likely to be the ‘best’ model than

250 model 1. The aforementioned authors have also suggested that in cases where a number of
251 models exhibit small evidence ratios, multi-model inference should be employed to
252 identify the relative importance of each of the variables (metrics) across all, or an
253 appropriate subset of, models. An analogous weight of evidence approach was thus
254 adopted for selecting those metrics that exhibited the most pronounced and consistent
255 inter-annual differences, based on their relative importance among the models in the $\Delta_i \leq 2$
256 subset. Only those metrics which occurred in >50% of the models in this subset were
257 selected.

258 It is recognised that the above approach to metric selection can only fit linear
259 combinations of the fish metrics to the model matrix. The second approach to metric
260 selection thus employed the BEST routine in PRIMER, which is a less constrained, fully
261 non-parametric method which caters for non-linear functions (Clarke and Ainsworth,
262 1993). A similar structure for identifying sets of near optimum models through the BEST
263 procedure might have been adopted (for example, by cutting off the subset of models at a
264 level of correlation considered significant by the global BEST test) but, in the present case,
265 we elected to simply use BEST in a secondary capacity to detect any metrics that the linear
266 DISTLM approach may have missed. This second approach, in which the reference
267 (model) resemblance matrix and complementary set of explanatory fish metric residual
268 data were the same as those used in the DISTLM routine, employed the BIOENV or
269 BVSTEP procedures in the BEST routine to search for that subset of fish metrics whose
270 pattern of rank order of resemblances between samples best matched that defined by the
271 model matrix of differences between years. In each case, the null hypothesis of no
272 similarities in rank order pattern between the complementary matrices was rejected if the
273 significance level (p) associated with the test statistic (Spearman's rank 'matrix
274 correlation' coefficient [ρ_s]) was ≤ 0.05 (Clarke et al., 2008). The extent of any significant

275 differences was determined by the magnitude of ρ_s , i.e. values close to zero indicate little
276 correlation in rank order pattern whereas those close to +1 indicated a near perfect
277 agreement. BIOENV was used to search all possible metric combinations for the 21 and 41
278 m and gill net data sets, whilst the far larger number of samples in the 102-133 m data set
279 necessitated the application of the BVSTEP routine, which searches only a subset of
280 possible metric combinations. The forward selection/backward elimination algorithm of
281 BVSTEP was repeated multiple times, starting with different, randomly selected subsets of
282 one to six metrics, to minimise the chances of not detecting the most suitable subset
283 (Clarke and Warwick, 1998).

284 Finally, a weight of evidence approach was adopted for consolidating, into a single
285 set, those metrics which were consistently identified as among the 'best' in the DISTLM
286 and BIOENV/BVSTEP analyses of the 21, 41 and 102-133 m data sets. Thus, a metric was
287 selected for inclusion in the nearshore index of estuarine health if it was identified by more
288 than one of the six analyses. Given the small number of metrics identified by the DISTLM
289 and BIOENV analyses of the gill net data set, and the fact that only two metrics were
290 selected by both analyses, the decision rule for metric selection was modified to include a
291 metric in the offshore index if it was identified by either of the two analyses.

292

293 **3. Results**

294 *3.1. Nearshore data sets*

295 The DISTLM analysis of the fish metric data derived from the 21 m data set
296 identified eight metrics (*No species*, *Dominance*, *Prop trop spec*, *No trop spec*, *Prop trop*
297 *gen*, *Prop est spawn*, *Prop P. olorum*, *Tot no P. olorum*) as $AIC_{c(\min)}$, i.e. as the
298 combination of metrics that best modelled the 0-1 model matrix and thus exhibited the
299 most consistent inter-annual differences. However, the Akaike weights for each of the

300 resultant models revealed that none had a high probability of being the single best, and the
301 application of multi-model inference was thus shown to be appropriate. A subset of 20
302 models with r^2 values ranging between 0.194 and 0.216 were identified as being within
303 two units of $AIC_{c(\min)}$ ($\Delta_i \leq 2$), and were thus also considered to be substantially supported
304 by the evidence (Table 4). The metrics that occurred at a relative frequency of >50%
305 among the models in this subset, and which were thus considered to have been selected by
306 the DISTLM routine, are listed in Table 5.

307 Similarly, the results of the DISTLM analysis carried out on the fish metric data
308 calculated from the 41 m data set (Appendix B) demonstrated that a model containing
309 seven metrics (*Prop trop spec*, *No trop spec*, *Prop detr*, *No benthic*, *Prop est spawn*, *No*
310 *est spawn*, *Prop P. olorum*) was the estimated ‘best’ ($AIC_{c(\min)}$), although a set of 66
311 models with r^2 values ranging from 0.237 to 0.329 were also identified as having
312 substantial support from the evidence ($\Delta_i \leq 2$). Akaike weights again revealed that none of
313 these fish metric combinations had a high probability of being the single best model. The
314 metrics that occurred at a relative frequency of >50% among the models in the $\Delta_i \leq 2$
315 subset are highlighted in Table 5.

316 DISTLM of the fish metric data calculated from the 102-133 m data set identified a
317 model containing nine metrics (*No species*, *Dominance*, *Prop trop spec*, *No trop spec*,
318 *Prop detr*, *Prop benthic*, *No benthic*, *Feed guild comp*, *No est spawn*) as the estimated
319 ‘best’ ($AIC_{c(\min)}$), although a set of 51 models with r^2 values ranging from 0.133 to 0.145
320 were also identified as having substantial support from the evidence (Appendix C). Table 5
321 again lists those metrics which occurred at a relative frequency of >50% among the models
322 in the $\Delta_i \leq 2$ subset.

323 BIOENV determined that, for the 21 m data set, the metrics *No trop spec*, *Prop*
324 *detr*, *Prop P. olorum* and *Tot no P. olorum* best matched the underlying pattern of rank

325 order resemblances between all pairs of samples in the model matrix ($\rho_s = 0.128$, $p = 0.01$;
326 Table 5) and thus differed the most consistently between years. For the 41 m data set,
327 BIOENV showed that *No trop gen*, *Prop detr*, *Prop benthic* and *Prop est spawn* were most
328 highly correlated with the model matrix ($\rho_s = 0.176$, $p = 0.01$), while for the 102-133 m
329 data set, BVSTEP identified the metrics *Prop trop spec*, *No benthic* and *No est spawn* as
330 being the best matched to the inter-annual model matrix ($\rho_s = 0.071$, $p = 0.001$). Although
331 each of the above correlations were significant, their extents were low in all cases, thus
332 indicating a weak match between the inter-annual patterns exhibited by the fish metrics
333 and those defined by the model matrix. This agrees with the findings of the DISTLM
334 approach, where r^2 values were also low, noting that r^2 and ρ are broadly comparable since
335 the latter is a matrix correlation, not a direct correlation.

336 Given the above findings, neither DISTLM nor BIOENV/BVSTEP alone could be
337 considered to have selected a definitive, best set of fish metrics for the nearshore waters of
338 the Swan Estuary. Consideration of the combined outputs of these analyses via a weight of
339 evidence approach was therefore appropriate for identifying the most reliable, informative
340 metric subset from which to build a nearshore index of estuarine health. The set of 11
341 metrics selected for inclusion in this index, namely those selected by more than one of the
342 six analyses, are shown in Table 5.

343

344 3.2. Offshore data set

345 The estimated ‘best’ model ($AIC_{c(\min)}$) identified by DISTLM as that which
346 demonstrated the most consistent inter-annual differences in the offshore waters of the
347 Swan Estuary contained the fish metrics *No species*, *No trop spec*, *No trop gen*, *Prop*
348 *benthic* and *Prop est spawn*. However, a subset of 66 models with r^2 values ranging
349 between 0.098 and 0.329 were again identified as having substantial support from the

350 evidence (Appendix D). As for the nearshore data sets, Akaike weights demonstrated that
351 none of these models had a high probability of being the single best. Selection of those
352 metrics occurring at a relative frequency of >50% among the models in this subset
353 generated the set of metrics highlighted in Table 6.

354 The BIOENV routine identified a set of five metrics (*Sh-div*, *No trop spec*,
355 *No trop gen*, *Prop detr* and *Prop benthic*) as being best matched to the model matrix of
356 inter-annual differences for the offshore data set ($\rho_s = 0.068$, $p = 0.07$; Table 6). Although
357 this correlation was weak, it was close to statistical significance at $p = 0.05$, and was thus
358 accepted for further consideration as part of the broader, evidence-based approach for
359 constructing the offshore health index. As only two metrics were selected by both the
360 DISTLM and BIOENV analyses of the gill net data set, the modified decision rule, to
361 select a metric for inclusion in the offshore index if it was identified by either of the two
362 analyses, subsequently generated a set of seven metrics (Table 6).

363

364 **4. Discussion**

365 Multi-metric biotic indices derived using an objective, statistical approach to
366 metric selection are widely regarded as being more robust than those based on expert
367 judgement alone (Hering et al., 2006; Roset et al., 2007). This study has produced a
368 generally applicable and multifaceted statistical approach for selecting the most responsive
369 and parsimonious subset of metrics for inclusion in a biotic index of ecosystem health. In
370 particular, this novel methodology allows the objective selection of health index metrics in
371 situations where independent data on ecosystem condition is unavailable, and can be
372 applied to any type of biota in any ecosystem. Moreover, by modifying the model matrix
373 to reflect available information, this approach could equally be applied to any situation in

374 which there is sound evidence for specific patterns or directions of change in the health of
375 an ecosystem over time or space.

376 In addition to the above, the current approach to metric selection also adheres to a
377 range of accepted recommendations for multi-metric index development that have been
378 documented in the relevant literature. Firstly, as recommended by Roset et al. (2007), the
379 metrics selected for inclusion in the ecosystem health index were chosen from an initial,
380 large candidate list using statistical tests of metric redundancy and sensitivity. Secondly, as
381 recommended by Hering et al. (2006) among others, the current approach excluded
382 erratically variable and highly correlated metrics in order to increase the reliability and
383 reduce the redundancy, respectively, of the resultant candidate metric set. Finally,
384 selection from among those remaining candidate metrics was carried out using statistical
385 testing of metric sensitivity to a model matrix, the latter of which can readily be tailored to
386 reflect a range of spatio-temporal trends.

387 The novel statistical approach adopted here, which employed a combination of
388 multivariate analyses and information-theoretic multi-model inference techniques, allowed
389 metrics to be selected according to the weight of evidence from multiple analyses of
390 numerous data sets, each of which was collected over differing periods and employed
391 divergent sampling techniques.

392 The adoption of novel statistical approaches for selecting metrics requires that the
393 use of these techniques be justified. Although the use of AIC and AIC_c for establishing the
394 importance of predictor variables in ‘explaining’ the underlying patterns in a response
395 cloud has been criticised by some authors (Link and Barker, 2006; Murray and Conner,
396 2009), Burnham and Anderson (2002) have shown that the relative importance of each
397 variable may be calculated by summing the Akaike weights for each model containing the
398 variable of interest and calculating ratios of those summed weights. This enables variables

399 to be ranked and selected according to their relative importance among multiple competing
400 models. In the present case, however, direct calculation of the relative importance of
401 variables (fish metrics) in the manner outlined above was invalid, as individual metrics
402 were not balanced in terms of the frequency with which they occurred among multiple
403 models in the output of the DISTLM routine. Therefore, the current study has adapted this
404 method by ranking the relative importance of individual metrics according to their relative
405 frequency among the likely 'best' ($\Delta_i \leq 2$) subset of models identified by DISTLM. Given
406 that all possible combinations of metrics have been tested and that some metrics occurred
407 more consistently than others among this 'best' subset, the weight of evidence suggests that
408 metrics which are present among >50% of those models are likely to be the most
409 consistently sensitive to inter-annual differences in estuarine condition, and thus most
410 appropriate for inclusion in an estuarine health index. Although the selection of variables
411 via exhaustive testing of all possible models has been identified as 'data dredging' and
412 cautioned against (Burnham and Anderson, 2002), the aim in the present case was not to
413 determine statistically significant explanatory variables and thus fit parameters to model
414 causative relationships, but rather to identify the most useful signals from which to
415 construct an estuarine health index, which will subsequently be validated using larger data
416 sets. The weight of evidence approach adopted in this study thus accounts for model
417 uncertainty and is compatible with the ideological demands of constructing a multi-metric
418 index that integrates information from a range of attributes of the fish community.

419 The Swan Estuary is an example of one of the many estuarine systems throughout
420 south-western Australia and, indeed, the world, for which robust, independent data on
421 ecosystem condition are not available at appropriate spatio-temporal scales. Unlike the
422 situation for many estuaries throughout Europe, the United States and South Africa, there
423 is thus no objective framework against which the sensitivity of candidate fish metrics for a

424 biotic index of ecosystem health for these systems might be assessed. Existing indicators
425 developed for the Swan Estuary focus on various aspects of water quality, (e.g. salinity,
426 temperature, total suspended solids, the concentrations of chlorophyll *a* and several key
427 nutrients) and counts of various phytoplankton groups. However, they provide little or no
428 information on the ecological status of the estuarine fauna and exhibit trends which are
429 highly inconsistent, often contrary and difficult to interpret (Henderson and Kuhnert, 2006;
430 Kuhnert and Henderson, 2006).

431 When the current approach was applied to the specific example of the fish fauna in
432 the Swan Estuary, the respective sets of 11 and seven metrics selected for the nearshore
433 and offshore waters were shown to represent a broad range of fish community
434 characteristics including species composition and diversity, trophic structure, life history
435 and habitat functions and, in the case of the nearshore index, a potential sentinel species.
436 Biotic indices constructed from a broad range of metrics such as this are more likely to
437 reflect the integrated ecological effects of multiple and diverse stressors, and thus reveal
438 their impacts on the condition of the estuary as a whole (Barbour et al., 1995). These
439 metric sets are currently being used to construct a multi-metric health index for the Swan
440 Estuary (the first such scheme to be developed for assessing and monitoring the health of
441 estuaries in Australia), whose sensitivity and reliability will be tested in subsequent studies

442 Despite the prior elimination of highly correlated metrics to reduce redundancy
443 among the candidate metric set for the Swan Estuary fish fauna, the results of the distance-
444 based linear modelling analyses of multiple data sets highlighted considerable redundancy
445 among the remaining candidate metrics, and indicated substantial uncertainty regarding the
446 particular subset of metrics that best responded to inter-annual differences. Moreover, the
447 consistently low r^2 and ρ_s values from the DISTLM and BIOENV/BVSTEP analyses,
448 respectively, revealed that no single combination of metrics explained a large proportion

449 of the inter-annual patterns in the model resemblance matrix. Therefore, for each of the
450 nearshore and offshore data sets analysed, acceptance of a single ‘best’ model was
451 inappropriate, and weight of evidence-based multi-model inference techniques were thus
452 applied to identify the set of metrics whose responses were most consistent over time and
453 across data sets.

454 It is universally recognised, however, that the final suite of metrics selected for
455 inclusion in a multi-metric index should include those that are sensitive to human
456 disturbance (Barbour et al., 1995; United States Environmental Protection Agency, 2006;
457 Roset et al., 2007; Niemeijer and de Groot, 2008). Thus, while the current approach
458 provides an avenue for circumventing any *a priori* demonstration of the relationships
459 between the selected metrics and independent measures of anthropogenic degradation (i.e.
460 where the latter data is not available), it should be reiterated that, in cases such as these,
461 *a posteriori* tests of metric sensitivity, redundancy and consistency are essential to
462 demonstrate their ecological relevance and robustness before they can be used to construct
463 a health index. This is the subject of continuing research for the example of the Swan
464 Estuary presented in this study.

465

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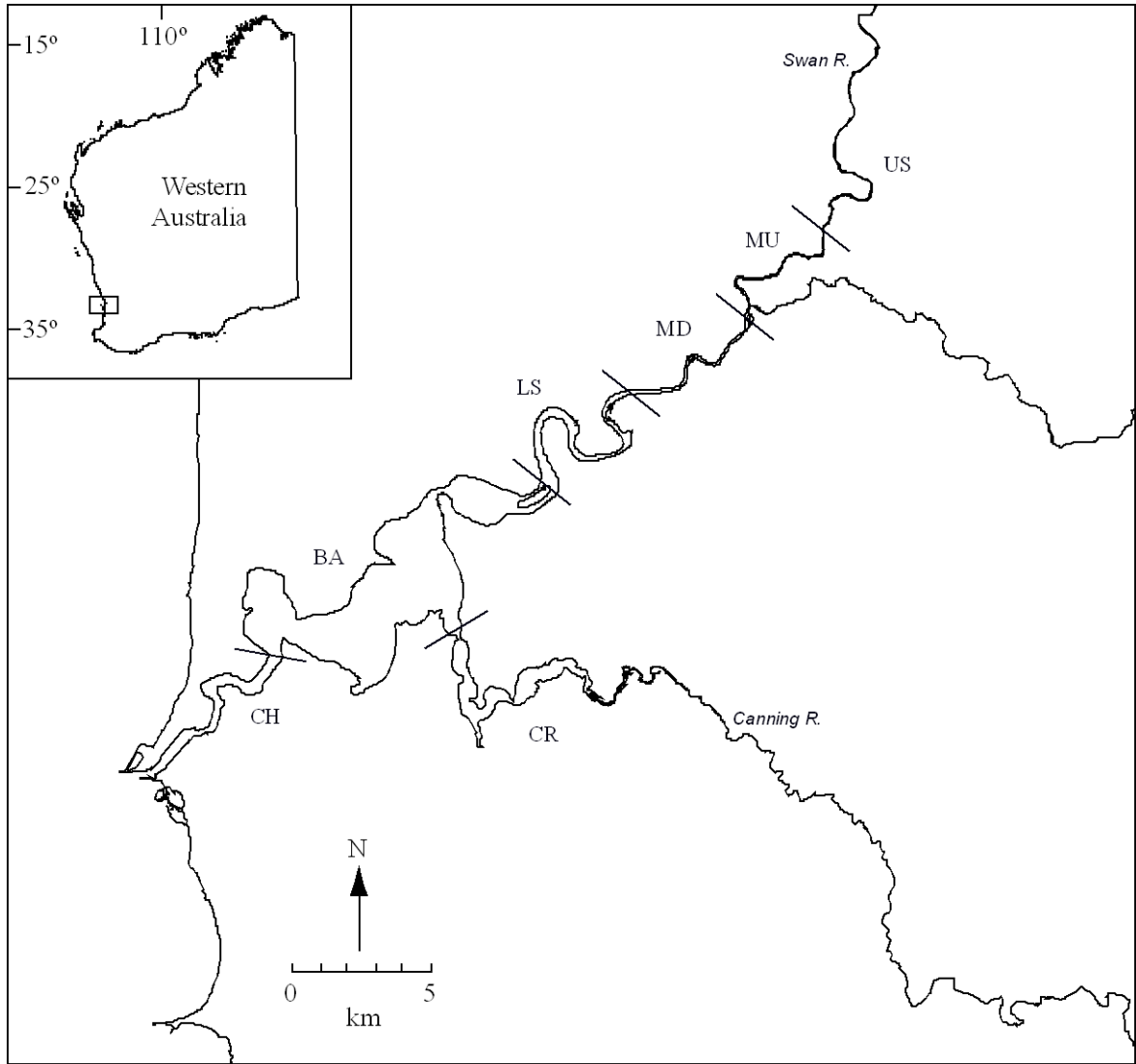
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654 **Figure Legends**

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656 **Fig. 1.** Location of the Swan Estuary, Western Australia (inset), illustrating the regions of
657 the estuary in which historical and current sampling of the estuarine fish community was
658 carried out. CH = Channel, BA = Basin, CR = Canning River, LS = Lower Swan River,
659 MD = Middle-Downstream Swan River, MU = Middle-Upstream Swan River, US =
660 Upper Swan River.



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672 **Table 1**

673 Fish species abundance data sets employed in the selection of metrics sensitive to temporal
 674 ecosystem change in the Swan Estuary, illustrating the regions of that system sampled
 675 seasonally during each study and the methods employed to sample them. CH = Channel,
 676 BA = Basin, CR = Canning River, LS = Lower Swan River, MD = Middle-Downstream
 677 Swan River, MU = Middle-Upstream Swan River, US = Upper Swan River. Locations of
 678 the regions of the Swan Estuary are shown in Fig. 1.

Study (Period)	Sampling method			
	Nearshore waters			Offshore waters
	21.5 m seine net	41.5 m seine net	102-133 m seine net	Gill net
	21.5 m long, 1.5 m deep, 9 mm mesh (wings), 3 mm mesh (pocket)	41.5 m long, 1.5 m deep, 25 mm mesh (wings), 9 mm mesh (pocket)	102.5-133 m long, 2 m deep 25.4 mm mesh (wings), 15.9 mm mesh (pocket)	6-8 x 20 m-long panels, Mesh sizes 35-127 mm in increments of 12-16 mm
Loneragan ^a (1976-1982)			CH, BA, CR, LS, MD, MU, US	
Sarre ^b (1993-1994)				LS, MD, MU
Kanandjembo ^c (1995-1997)		LS, MD		LS, MD
Hoeksema ^d (1999-2001)	MD, MU, US			
Hoeksema ^e (2003-2004)		LS, MD		LS, MD, MU
Valesini ^f (2005-2007)	MD, MU, US			
Current study (2007-2009)		LS, MD		LS, MD, MU

679 ^aLoneragan et al., 1989; Loneragan and Potter 1990; ^bSarre, unpublished data; ^cKanandjembo et al., 2001; ^d
 680 Hoeksema and Potter 2006; ^eHoeksema, unpublished data; ^fValesini et al., unpublished data.

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688 **Table 2**

689 List of candidate metrics for possible inclusion in a biotic index of estuarine health for the
 690 Swan Estuary. ‘Trophic Specialist’ comprises the feeding mode guilds Zooplanktivore,
 691 Zoobenthivore, Herbivore, Piscivore; ‘Trophic Generalist’ comprises the feeding mode
 692 guilds Omnivore, Opportunist; ‘Benthic’ comprises the habitat guilds Benthopelagic,
 693 Small Benthic, Demersal; ‘Estuarine Spawner’ comprises the habitat guilds Estuarine
 694 species and Semi-Anadromous. * Where appropriate, two variants of each metric were
 695 tested, namely ‘number of taxa’ and ‘proportion of total individuals’ (variants not shown
 696 for brevity).

Metric	Metric description*
<i>Species diversity / composition / abundance</i>	
Species richness	Total number of species present
Dominance	Number of species comprising 90% of total individuals
Total density	Total number of individuals
Introduced	Contribution of alien/introduced species
Native	Contribution of native species
Shannon diversity	Shannon Diversity Index
Pielou’s evenness	Pielou’s Evenness Index
<i>Trophic structure</i>	
Trophic Specialist	Contribution of trophic specialist species
Carnivore	Contribution of carnivorous species
Piscivore	Contribution of piscivorous species
Omnivore	Contribution of omnivorous species
Opportunist	Contribution of opportunist species
Trophic Generalist	Contribution of trophic generalist species
Detritivore	Contribution of detritivorous species
Feeding Guild Composition	The number of different trophic guilds present (after Coates et al., 2007)
<i>Habitat / life history function</i>	
Benthic	Contribution of benthic associated species
Estuarine Spawner	Contribution of estuarine spawning species
Estuarine Resident	Contribution of estuarine resident species
<i>Sentinel species</i>	
<i>P. olorum</i>	Contribution of <i>Pseudogobius olorum</i>

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701 **Table 3**

702 Refined list of candidate metrics for possible inclusion in a biotic index of estuarine health

703 for the Swan Estuary.

Metric	Metric code	Metric description
<i>Species diversity / composition / abundance</i>		
Species richness	<i>No species</i>	Total number of species present
Dominance	<i>Dominance</i>	No. of species comprising 90% of total individuals
Shannon diversity	<i>Sh-div</i>	Shannon's diversity index
<i>Trophic structure</i>		
Proportion of trophic specialists	<i>Prop trop spec</i>	Trophic specialists as a proportion of total individuals
Number of trophic specialists	<i>No trop spec</i>	Number of trophic specialist species
Proportion of trophic generalists	<i>Prop trop gen</i>	Trophic generalists as a proportion of total individuals
Number of trophic generalists	<i>No trop gen</i>	Number of trophic generalist species
Proportion of detritivores	<i>Prop detr</i>	Detritivores as a proportion of total individuals
Number of detritivores	<i>No detr</i>	Number of detritivorous species
Feeding Guild Composition	<i>Feed guild comp</i>	Number of different trophic guilds present
<i>Habitat / life history function</i>		
Proportion of benthic species	<i>Prop benthic</i>	Benthic associated as a proportion of total individuals
Number of benthic species	<i>No benthic</i>	Number of benthic associated species
Proportion of estuarine spawners	<i>Prop est spawn</i>	Estuarine spawners as a proportion of total individuals
Number of estuarine spawning species	<i>No est spawn</i>	Number of estuarine spawning species
Proportion of estuarine residents	<i>Prop est res</i>	Estuarine residents as a proportion of total individuals
Number of estuarine resident species	<i>No est res</i>	Number of estuarine resident species
<i>Sentinel species</i>		
Proportion of <i>P. olorum</i>	<i>Prop P. olorum</i>	<i>P. olorum</i> as a proportion of total individuals
Total density of <i>P. olorum</i>	<i>Tot no P. olorum</i>	Total abundance (density) of <i>P. olorum</i>

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714 **Table 4**

715 The subset of models (fish metric combinations) identified as being substantially
 716 supported by evidence ($\Delta_i \leq 2$) from distance-based linear modelling of the 21 m data set.
 717 Selection criterion (AIC_c) and associated measures of the evidence in favour of each model
 718 are presented. The estimated ‘best’ model, termed $AIC_{c(\min)}$, is italicised.

AIC_c	Number of metrics	Metrics selected *	AIC_c difference (Δ_i)	log-likelihood	Akaike weight (w_i)	Evidence ratio
<i>-338.28</i>	8	<i>1,2,4,5,6,11,13,14</i>	<i>0</i>	<i>1.00</i>	<i>0.09</i>	<i>1.00</i>
-338.01	7	1,4,5,6,11,13,14	0.27	0.87	0.08	1.14
-337.71	8	1,3,4,5,6,11,13,14	0.57	0.75	0.07	1.33
-337.44	9	1,2,4,5,6,11,12,13,14	0.84	0.66	0.06	1.52
-337.38	7	4,5,7,11,12,13,14	0.90	0.64	0.06	1.57
-337.32	7	4,5,6,7,11,13,14	0.96	0.62	0.06	1.62
-337.29	8	2,4,5,6,7,11,13,14	0.99	0.61	0.06	1.64
-337.10	9	1,3,4,5,6,11,12,13,14	1.18	0.55	0.05	1.80
-337.00	8	1,4,5,6,11,12,13,14	1.28	0.53	0.05	1.90
-336.97	8	3,4,5,6,7,11,13,14	1.31	0.52	0.05	1.93
-336.76	9	1,2,4,5,6,9,11,13,14	1.52	0.47	0.04	2.14
-336.69	8	3,4,5,7,11,12,13,14	1.59	0.45	0.04	2.21
-336.59	8	1,4,5,6,9,11,13,14	1.69	0.43	0.04	2.33
-336.57	8	2,4,5,7,11,12,13,14	1.71	0.43	0.04	2.35
-336.37	9	1,2,4,5,6,7,11,13,14	1.91	0.38	0.04	2.60
-336.36	8	1,4,5,6,7,11,13,14	1.92	0.38	0.04	2.61
-336.35	9	1,2,4,5,6,10,11,13,14	1.93	0.38	0.04	2.62
-336.30	9	2,4,5,6,7,11,12,13,14	1.98	0.37	0.03	2.69
-336.29	9	1,2,4,5,6,8,11,13,14	1.99	0.37	0.03	2.70
-336.28	9	1,3,4,5,6,9,11,13,14	2.00	0.37	0.03	2.72

719 * **Metric Numbers (see Table 3 for explanation of metric abbreviations):** 1. *No species*; 2. *Dominance*; 3. *Sh-div*; 4.
 720 *Prop trop spec*; 5. *No trop spec*; 6. *No trop gen*; 7. *Prop detr*; 8. *Prop benthic*; 9. *No benthic*; 10. *Feed guild comp*; 11.
 721 *Prop est spawn*; 12. *No est spawn*; 13. *Prop P. olorum*; 14. *Tot no P. olorum*

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730 **Table 5**

731 Summary of the fish metrics selected by the DISTLM and BIOENV/BVSTEP analyses of
 732 the nearshore data sets (light highlight), including those metrics selected by multiple
 733 analyses and thus identified as appropriate for incorporation into a nearshore estuarine
 734 health index for the Swan Estuary (dark highlight). Numbers shown represent the relative
 735 frequency (%) of the metric among the ‘best’ model subset. See Table 3 for explanation of
 736 metric abbreviations.

Metric	21 m data set		41 m data set		102-133 m data set		Selected
	DISTLM	BIOENV	DISTLM	BIOENV	DISTLM	BVSTEP	
<i>No species</i>	65		58		100		
<i>Dominance</i>	45		3		63		
<i>Sh-div</i>	25		6		39		
<i>Prop trop spec</i>	100		91		57		
<i>No trop spec</i>	100		100		100		
<i>No trop gen</i>	85		27		29		
<i>Prop detr</i>	65		71		100		
<i>Feed guild comp</i>	5		5		100		
<i>Prop benthic</i>	15		56		86		
<i>No benthic</i>	5		86		100		
<i>Prop est spawn</i>	100		53		39		
<i>No est spawn</i>	85		59		100		
<i>Prop P. olorum</i>	100		73		20		
<i>Tot no P. olorum</i>	100		5		12		

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739 **Table 6**

740 Fish metrics selected by the DISTLM or BIOENV analyses of the offshore data set (light
 741 highlight) and thus identified as appropriate for incorporation into an offshore estuarine
 742 health index (dark highlight). Numbers shown represent the relative frequency (%) of the
 743 metric among the ‘best’ model subset. See Table 3 for explanation of metric abbreviations.

Metric	Gill net data set		Selected
	DISTLM	BIOENV	
<i>No species</i>	80		
<i>Dominance</i>	24		
<i>Sh-div</i>	39		
<i>Prop trop spec</i>	12		
<i>No trop spec</i>	88		
<i>No trop gen</i>	42		
<i>Prop detr</i>	39		
<i>Feed guild comp</i>	44		
<i>Prop benthic</i>	100		
<i>No benthic</i>	18		
<i>Prop est spawn</i>	100		
<i>No est spawn</i>	21		

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756 **Appendices**

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758 **Appendix A.** List of fish species identified from the Swan Estuary during previous

759 (1976-2007) and current (2007-2009) studies, and the functional guilds to which they were

760 allocated. Abbreviations: P – large pelagic; D – demersal (species closely associated with

761 substrate, rocks or weed); BP – benthic-pelagic; SP – small pelagic; SB – small benthic;

762 MS – marine straggler; MM – marine migrant (includes marine estuarine opportunists);

763 SA – semi-anadromous; ES – estuarine species; FM – freshwater migrant or straggler; PV

764 – piscivore; ZB – zoobenthivore; ZP – zooplanktivore; DV – detritivore; OV – omnivore;

765 HV – herbivore; OP – opportunist.

Species name	Common name	Habitat	Estuarine Use	Feeding Mode
<i>Carcharinas leucas</i>	Bull shark	P	MS	PV
<i>Myliobatis australis</i>	Southern eagle ray	D	MS	ZB
<i>Elops machnata</i>	Giant herring	BP	MS	PV
<i>Hyperlophus vittatus</i>	Sandy sprat	SP	MM	ZP
<i>Spratelloides robustus</i>	Blue sprat	SP	MM	ZP
<i>Sardinops neopilchardus</i>	Australian pilchard	P	MS	ZP
<i>Sardinella lemuru</i>	Scaly mackerel	P	MS	ZP
<i>Nematalosa vlaminghi</i>	Perth herring	BP	SA	DV
<i>Engraulis australis</i>	Southern anchovy	SP	ES	ZP
<i>Galaxias occidentalis</i>	Western minnow	SB	FM	ZB
<i>Carassius auratus</i>	Goldfish	BP	FM	OV
<i>Cnidoglanis macrocephalus</i>	Estuarine cobbler	D	MM	ZB
<i>Tandanus bostocki</i>	Freshwater cobbler	D	FM	ZB
<i>Hyporhamphus melanochir</i>	Southern sea garfish	P	ES	HV
<i>Hyporhamphus regularis</i>	Western river garfish	P	FM	HV
<i>Gambusia holbrooki</i>	Mosquito fish	SP	FM	ZB
<i>Atherinosoma elongata</i>	Elongate hardyhead	SP	ES	ZB
<i>Leptatherina presbyteroides</i>	Presbyter's hardyhead	SP	MM	ZP
<i>Atherinomorus vaigensis</i>	Ogilby's hardyhead	SP	MM	ZB
<i>Craterocephalus mugiloides</i>	Mugil's hardyhead	SP	ES	ZB
<i>Leptatherina wallacei</i>	Wallace's hardyhead	SP	ES	ZP
<i>Cleidopus gloriamaris</i>	Pineapplefish	D	MS	ZB
<i>Stigmatophora nigra</i>	Wide-bodied pipefish	D	MS	ZB
<i>Vanacampus phillipi</i>	Port Phillip pipefish	D	MS	ZB
<i>Phyllopteryx taeniolatus</i>	Common seadragon	D	MS	ZB
<i>Hippocampus angustus</i>	Western Australian seahorse	D	MS	ZP
<i>Stigmatophora argus</i>	Spotted pipefish	D	MS	ZP
<i>Urocampus carinirostris</i>	Hairy pipefish	D	ES	ZP
<i>Filicampus tigris</i>	Tiger pipefish	D	MS	ZP
<i>Pugnaso curtirostris</i>	Pugnose pipefish	D	MS	ZP
<i>Gymnapistes marmoratus</i>	Devilfish	D	MS	ZB
<i>Chelidonichthys kumu</i>	Red gurnard	D	MS	ZB
<i>Platycephalus laevigatus</i>	Rock flathead	D	MS	PV
<i>Platycephalus endrachtensis</i>	Bar-tailed flathead	D	ES	PV
<i>Leviprora inops</i>	Long-head flathead	D	MS	PV
<i>Platycephalus speculator</i>	Southern blue-spotted flathead	D	ES	PV
<i>Pegasus lancifer</i>	Sculptured seamothe	D	MS	ZB
<i>Amniataba caudavittata</i>	Yellow-tail trumpeter	BP	ES	OP

<i>Pelates octolineatus</i>	Eight-line trumpeter	BP	MM	OV
<i>Pelsartia humeralis</i>	Sea trumpeter	BP	MS	OV
<i>Edelia vittata</i>	Western pygmy perch	BP	FM	ZB
<i>Apogon rueppelli</i>	Gobbleguts	BP	ES	ZB
<i>Siphamia cephalotes</i>	Woods siphonfish	BP	MS	ZB
<i>Sillago bassensis</i>	Southern school whiting	D	MS	ZB
<i>Sillago burrus</i>	Trumpeter whiting	D	MM	ZB
<i>Sillaginodes punctata</i>	King George whiting	D	MM	ZB
<i>Sillago schomburgkii</i>	Yellow-finned whiting	D	MM	ZB
<i>Sillago vittata</i>	Western school whiting	D	MM	ZB
<i>Pomatomus saltatrix</i>	Tailor	P	MM	PV
<i>Trachurus novaezelandiae</i>	Yellowtail scad	P	MS	ZB
<i>Pseudocaranx dentex</i>	Silver trevally	BP	MM	ZB
<i>Pseudocaranx wrightii</i>	Sand trevally	BP	MM	ZB
<i>Arripis georgianus</i>	Australian herring	P	MM	PV
<i>Arripis esper</i>	Southern Australian salmon	P	MS	PV
<i>Gerres subfasciatus</i>	Roach	BP	MM	ZB
<i>Pagrus auratus</i>	Snapper	BP	MM	ZB
<i>Acanthopagrus butcheri</i>	Southern black bream	BP	ES	OP
<i>Rhabdosargus sarba</i>	Tarwhine	BP	MM	ZB
<i>Argyrosomus japonicus</i>	Mulloway	BP	MM	PV
<i>Pampaneus spilurus</i>	Black-saddled goatfish	D	MS	ZB
<i>Enoplosus armatus</i>	Old wife	D	MS	ZB
<i>Aldrichetta forsteri</i>	Yellow-eye mullet	P	MM	OV
<i>Mugil cephalus</i>	Sea mullet	P	MM	DV
<i>Sphyrnaena obtusata</i>	Striped barracuda	P	MS	PV
<i>Haletta semifasciata</i>	Blue weed whiting	D	MS	OV
<i>Siphonognathus radiatus</i>	Long-rayed weed whiting	D	MS	OV
<i>Neoodax baltatus</i>	Little weed whiting	D	MS	OV
<i>Odax acroptilus</i>	Rainbow cale	D	MS	OV
<i>Parapercis haackei</i>	Wavy grubfish	D	MS	ZB
<i>Petroscirtes breviceps</i>	Short-head sabre blenny	SB	MS	OV
<i>Omobranchus germaini</i>	Germain's blenny	SB	MS	ZB
<i>Parablennius intermedius</i>	Horned blenny	D	MS	ZB
<i>Istiblennius meleagris</i>	Peacock rockskipper	D	MS	HV
<i>Cristiceps australis</i>	Southern crested weedfish	D	MS	ZB
<i>Pseudocalliurichthys goodladi</i>	Longspine stinkfish	D	MS	ZB
<i>Eocallionymus papilio</i>	Painted stinkfish	D	MS	ZB
<i>Nesogobius pulchellus</i>	Sailfin goby	SB	MS	ZB
<i>Favonigobius lateralis</i>	Long-finned goby	SB	MM	ZB
<i>Afurcagobius suppositus</i>	Southwestern goby	SB	ES	ZB
<i>Pseudogobius olorum</i>	Blue-spot / Swan River goby	SB	ES	OV
<i>Amoya bifrenatus</i>	Bridled goby	SB	ES	ZB
<i>Callogobius mucosus</i>	Sculptured goby	SB	MS	ZB
<i>Callogobius depressus</i>	Flathead goby	SB	MS	ZB
<i>Papillogobius punctatus</i>	Red-spot goby	SB	ES	ZB
<i>Tridentiger trionocephalus</i>	Trident goby	SB	MS	ZB
<i>Pseudorhombus jenynsii</i>	Small-toothed flounder	D	MM	ZB
<i>Ammotretis rostratus</i>	Longsnout flounder	D	MM	ZB
<i>Ammotretis elongata</i>	Elongate flounder	D	MM	ZB
<i>Cynoglossus broadhursti</i>	Southern tongue sole	D	MS	ZB
<i>Acanthaluteres brownii</i>	Spiny-tailed leatherjacket	D	MS	OV
<i>Brachaluteres jacksonianus</i>	Southern pygmy leatherjacket	D	MS	OV
<i>Scobinichthys granulatus</i>	Rough leatherjacket	D	MS	OV
<i>Meuschenia freycineti</i>	Sixspine leatherjacket	D	MM	OV
<i>Monacanthus chinensis</i>	Fanbellied leatherjacket	D	MM	OV
<i>Eubalichthys mosaicus</i>	Mosaic leatherjacket	D	MS	OV
<i>Acanthaluteres vittiger</i>	Toothbrush leatherjacket	D	MS	OV
<i>Acanthaluteres spilomelanurus</i>	Bridled leatherjacket	D	MM	OV
<i>Torquigener pleurogramma</i>	Banded toadfish	BP	MM	OP
<i>Contusus breviceaudus</i>	Prickly toadfish	BP	MS	OP
<i>Polyspina piosae</i>	Orange-barred puffer	BP	MS	OP
<i>Diodon nichthemenus</i>	Globefish	D	MS	ZB
<i>Scorpius aequipinnis</i>	Sea sweep	P	MS	ZP
<i>Neatypus obliquus</i>	Footballer sweep	P	MS	ZP

767 **Appendix B.** The subset of models (fish metric combinations) identified as being
768 substantially supported by evidence ($\Delta_i \leq 2$) from distance-based linear modelling of the
769 41 m data set. Selection criterion (AIC_c) and associated measures of the evidence in favour
770 of each model are presented. The estimated ‘best’ model, termed $AIC_{c(\min)}$, is italicised.

AIC_c	Number of metrics	Metrics selected *	AIC_c difference (Δ_i)	Log-likelihood	Akaike weight (w_i)	Evidence ratio
<i>-111.54</i>	7	<i>4,5,7,9,11,12,13</i>	0	1.00	0.03	1.00
-111.48	7	4,5,7,8,9,12,13	0.06	0.97	0.03	1.03
-111.35	8	4,5,7,8,9,11,12,13	0.19	0.91	0.03	1.10
-111.19	6	4,5,7,8,12,13	0.35	0.84	0.02	1.19
-111.09	6	1,4,5,7,9,11	0.45	0.80	0.02	1.25
-111.04	6	1,4,5,6,9,11	0.50	0.78	0.02	1.28
-110.86	7	4,5,7,8,11,12,13	0.68	0.71	0.02	1.40
-110.72	5	1,4,5,9,11	0.82	0.66	0.02	1.51
-110.71	7	1,4,5,7,9,11,13	0.83	0.66	0.02	1.51
-110.68	7	4,5,6,7,8,12,13	0.86	0.65	0.02	1.54
-110.66	8	1,4,5,7,8,9,12,13	0.88	0.64	0.02	1.55
-110.62	7	1,4,5,6,9,11,13	0.92	0.63	0.02	1.58
-110.56	8	1,4,5,6,8,9,12,13	0.98	0.61	0.02	1.63
-110.44	6	4,5,7,9,11,12	1.10	0.58	0.02	1.73
-110.40	6	5,7,8,9,11,12,13	1.14	0.57	0.02	1.77
-110.35	6	5,7,8,9,12,13	1.19	0.55	0.02	1.81
-110.34	5	1,5,7,9,11	1.20	0.55	0.02	1.82
-110.32	5	5,7,8,12,13	1.22	0.54	0.02	1.84
-110.29	8	4,5,6,7,8,11,12,13	1.25	0.54	0.02	1.87
-110.28	7	1,4,5,8,9,12,13	1.26	0.53	0.02	1.88
-110.27	6	1,4,5,9,11,13	1.27	0.53	0.02	1.89
-110.20	6	4,5,7,9,12,13	1.34	0.51	0.02	1.95
-110.19	7	1,4,5,7,9,12,13	1.35	0.51	0.02	1.96
-110.16	5	1,4,5,6,9	1.38	0.50	0.01	1.99
-110.14	7	1,4,5,7,8,9,11	1.40	0.50	0.01	2.01
-110.12	8	1,4,5,7,9,11,12,13	1.42	0.49	0.01	2.03
-110.12	6	1,4,5,6,8,9	1.42	0.49	0.01	2.03
-110.12	5	1,4,5,7,9	1.42	0.49	0.01	2.03
-110.11	7	1,4,5,6,9,12,13	1.43	0.49	0.01	2.04
-110.10	7	1,4,5,6,8,9,11	1.44	0.49	0.01	2.05
-110.10	6	1,4,5,7,8,9	1.44	0.49	0.01	2.05
-110.09	7	1,4,5,6,8,9,13	1.45	0.48	0.01	2.06
-110.05	6	1,4,5,9,12,13	1.49	0.47	0.01	2.11
-109.99	7	1,4,5,9,11,12,13	1.55	0.46	0.01	2.17
-109.97	6	1,5,7,9,11,13	1.57	0.46	0.01	2.19
-109.96	8	1,4,5,6,8,9,11,13	1.58	0.45	0.01	2.20
-109.96	8	3,4,5,7,9,11,12,13	1.58	0.45	0.01	2.20
-109.96	8	1,4,5,7,8,9,11,13	1.58	0.45	0.01	2.20
-109.94	8	1,4,5,6,9,11,12,13	1.60	0.45	0.01	2.23
-109.92	9	1,4,5,7,8,9,11,12,13	1.62	0.44	0.01	2.25
-109.90	8	2,4,5,7,8,9,12,13	1.64	0.44	0.01	2.27
-109.89	8	4,5,7,8,9,12,13,14	1.65	0.44	0.01	2.28
-109.86	8	3,4,5,7,8,9,12,13	1.68	0.43	0.01	2.32

-109.85	7	1,4,5,7,8,9,13	1.69	0.43	0.01	2.33
-109.80	7	1,4,5,6,7,9,11	1.74	0.42	0.01	2.39
-109.80	9	1,4,5,6,8,9,11,12,13	1.74	0.42	0.01	2.39
-109.78	6	1,4,5,6,9,13	1.76	0.41	0.01	2.41
-109.75	8	4,5,6,7,8,9,12,13	1.79	0.41	0.01	2.45
-109.73	9	4,5,7,8,9,11,12,13,14	1.81	0.40	0.01	2.47
-109.73	7	5,7,8,9,11,12,13	1.81	0.40	0.01	2.47
-109.68	8	4,5,7,9,10,11,12,13	1.86	0.39	0.01	2.53
-109.65	6	4,5,6,7,8,13	1.89	0.39	0.01	2.57
-109.64	7	1,4,5,7,9,10,11	1.90	0.39	0.01	2.59
-109.64	7	4,5,7,8,12,13,14	1.90	0.39	0.01	2.59
-109.62	9	3,4,5,7,8,9,11,12,13	1.92	0.38	0.01	2.61
-109.61	7	2,4,5,7,8,12,13	1.93	0.38	0.01	2.62
-109.61	6	4,5,7,8,9,12	1.93	0.38	0.01	2.62
-109.60	6	1,4,5,7,9,13	1.94	0.38	0.01	2.64
-109.60	6	1,4,5,8,9,11	1.94	0.38	0.01	2.64
-109.59	7	1,3,4,5,7,9,11	1.95	0.38	0.01	2.65
-109.59	8	1,4,5,8,9,11,12,13	1.95	0.38	0.01	2.65
-109.59	7	1,4,5,7,9,11,12	1.95	0.38	0.01	2.65
-109.58	8	4,5,7,8,9,10,12,13	1.96	0.38	0.01	2.66
-109.58	9	4,5,6,7,8,9,11,12,13	1.96	0.38	0.01	2.66
-109.54	5	4,5,7,9,11	2.00	0.37	0.01	2.72
-109.54	7	1,4,5,7,8,12,13	2.00	0.37	0.01	2.72

771 * **Metric Numbers (see Table 3 for explanation of metric abbreviations):** 1. *No species*; 2. *Dominance*; 3. *Sh-div*; 4.
772 *Prop trop spec*; 5. *No trop spec*; 6. *No trop gen*; 7. *Prop detr*; 8. *Prop benthic*; 9. *No benthic*; 10. *Feed guild comp*; 11.
773 *Prop est spawn*; 12. *No est spawn*; 13. *Prop P. olorum*; 14. *Tot no P. olorum*

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787 **Appendix C.** The subset of models (fish metric combinations) identified as being
788 substantially supported by evidence ($\Delta_i \leq 2$) from distance-based linear modelling of the
789 102-133 m data set. Selection criterion (AIC_c) and associated measures of the evidence in
790 favour of each model are presented. The estimated ‘best’ model, termed $AIC_{c(\min)}$, is
791 italicised.

AIC_c	Number of metrics	Metrics selected *	AIC_c difference (Δ_i)	log-likelihood	Akaike weight (w_i)	Evidence ratio
<i>-638.51</i>	9	<i>1,2,4,5,7,8,9,10,12</i>	0	1.00	0.04	1.00
-638.23	8	1,4,5,7,8,9,10,12	0.28	0.87	0.03	1.15
-638.11	10	1,2,3,4,5,7,8,9,10,12	0.40	0.82	0.03	1.22
-637.94	9	1,2,5,7,8,9,10,11,12	0.57	0.75	0.03	1.33
-637.82	8	1,2,5,7,8,9,10,12	0.69	0.71	0.03	1.41
-637.75	10	1,2,4,5,7,8,9,10,12,13	0.76	0.68	0.03	1.46
-637.72	10	1,2,4,5,6,7,8,9,10,12	0.79	0.67	0.03	1.48
-637.70	9	1,2,5,6,7,8,9,10,12	0.81	0.67	0.03	1.50
-637.66	9	1,3,4,5,7,8,9,10,12	0.85	0.65	0.03	1.53
-637.58	10	1,2,4,5,7,8,9,10,11,12	0.93	0.63	0.02	1.59
-637.48	9	1,4,5,6,7,8,9,10,12	1.03	0.60	0.02	1.67
-637.42	10	1,2,5,6,7,8,9,10,11,12	1.09	0.58	0.02	1.72
-637.36	11	1,2,3,4,5,7,8,9,10,12,13	1.15	0.56	0.02	1.78
-637.29	10	1,2,4,5,7,8,9,10,12,14	1.22	0.54	0.02	1.84
-637.27	9	1,2,4,5,7,9,10,11,12	1.24	0.54	0.02	1.86
-637.22	9	1,2,3,5,7,8,9,10,12	1.29	0.52	0.02	1.91
-637.19	9	1,2,5,7,8,9,10,12,13	1.32	0.52	0.02	1.93
-637.18	10	1,2,3,5,7,8,9,10,11,12	1.33	0.51	0.02	1.94
-637.16	8	1,5,6,7,8,9,10,12	1.35	0.51	0.02	1.96
-637.16	11	1,2,3,4,5,6,7,8,9,10,12	1.35	0.51	0.02	1.96
-637.14	7	1,5,7,8,9,10,12	1.37	0.50	0.02	1.98
-637.12	8	1,2,4,5,7,9,10,12	1.39	0.50	0.02	2.00
-637.06	10	1,2,5,7,8,9,10,11,12,13	1.45	0.48	0.02	2.06
-637.03	9	1,4,5,7,8,9,10,12,14	1.48	0.48	0.02	2.10
-637.01	10	1,3,4,5,7,8,9,10,12,13	1.50	0.47	0.02	2.12
-637.01	11	1,2,3,4,5,7,8,9,10,11,12	1.50	0.47	0.02	2.12
-636.99	10	1,3,4,5,6,7,8,9,10,12	1.52	0.47	0.02	2.14
-636.93	10	1,2,3,5,6,7,8,9,10,12	1.58	0.45	0.02	2.20
-636.93	9	1,4,5,7,8,9,10,11,12	1.58	0.45	0.02	2.20
-636.92	11	1,2,3,4,5,7,8,9,10,12,14	1.59	0.45	0.02	2.21
-636.92	9	1,4,5,7,8,9,10,12,13	1.59	0.45	0.02	2.21
-636.90	9	1,3,5,6,7,8,9,10,12	1.61	0.45	0.02	2.24
-636.78	9	1,2,5,7,8,9,10,12,14	1.73	0.42	0.02	2.38
-636.77	8	1,3,5,7,8,9,10,12	1.74	0.42	0.02	2.39
-636.77	11	1,2,4,5,6,7,8,9,10,12,13	1.74	0.42	0.02	2.39
-636.75	10	1,2,5,6,7,8,9,10,12,13	1.76	0.41	0.02	2.41
-636.74	9	1,3,5,7,8,9,10,11,12	1.77	0.41	0.02	2.42
-636.71	10	1,2,3,4,5,7,9,10,11,12	1.80	0.41	0.02	2.46
-636.71	10	1,2,5,7,8,9,10,11,12,14	1.80	0.41	0.02	2.46
-636.70	8	1,2,5,7,9,10,11,12	1.81	0.40	0.02	2.47
-636.67	11	1,2,4,5,7,8,9,10,11,12,13	1.84	0.40	0.02	2.51

-636.66	11	1,2,4,5,6,7,8,9,10,11,12	1.85	0.40	0.02	2.52
-636.65	9	1,2,3,4,5,7,9,10,12	1.86	0.39	0.02	2.53
-636.64	10	1,3,4,5,7,8,9,10,12,14	1.87	0.39	0.02	2.55
-636.64	8	1,4,5,7,9,10,11,12	1.87	0.39	0.02	2.55
-636.60	11	1,2,3,5,6,7,8,9,10,11,12	1.91	0.38	0.01	2.60
-636.60	8	1,5,7,8,9,10,11,12	1.91	0.38	0.01	2.60
-636.60	10	1,2,3,5,7,8,9,10,12,13	1.91	0.38	0.01	2.60
-636.56	10	1,3,4,5,7,8,9,10,11,12	1.95	0.38	0.01	2.65
-636.55	9	1,2,5,6,7,9, 10,11,12	1.96	0.38	0.01	2.66
-636.54	10	1,3,5,6,7,8,9,10,11,12	1.97	0.37	0.01	2.68

792 * **Metric Numbers (see Table 3 for explanation of metric abbreviations):** 1. *No species*; 2. *Dominance*; 3. *Sh-div*; 4.
793 *Prop trop spec*; 5. *No trop spec*; 6. *No trop gen*; 7. *Prop detr*; 8. *Prop benthic*; 9. *No benthic*; 10. *Feed guild comp*; 11.
794 *Prop est spawn*; 12. *No est spawn*; 13. *Prop P. olorum*; 14. *Tot no P. olorum*

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814 **Appendix D.** The subset of models (fish metric combinations) identified as being
815 substantially supported by evidence ($\Delta_i \leq 2$) from distance-based linear modelling of the
816 gill net data set. Selection criterion (AIC_c) and associated measures of the evidence in
817 favour of each model are presented. The estimated ‘best’ model, termed $AIC_{c(\min)}$, is
818 italicised.

AIC_c	Number of metrics	Metrics selected *	AIC_c difference (Δ_i)	log-likelihood	Akaike weight (w_i)	Evidence ratio
<i>-240.16</i>	5	<i>1,5,6,8,11</i>	0	1.00	0.03	1.00
-239.97	6	1,5,7,8,10,11	0.19	0.91	0.03	1.10
-239.93	5	1,5,8,10,11	0.23	0.89	0.03	1.12
-239.85	6	1,5,6,8,10,11	0.31	0.86	0.03	1.17
-239.78	4	6,7,8,11	0.38	0.83	0.02	1.21
-239.58	5	1,5,7,8,11	0.58	0.75	0.02	1.34
-239.50	4	1,5,8,11	0.66	0.72	0.02	1.39
-239.49	7	1,2,3,5,6,8,11	0.67	0.72	0.02	1.40
-239.38	6	1,3,5,6,8,11	0.78	0.68	0.02	1.48
-239.30	3	6,8,11	0.86	0.65	0.02	1.54
-239.24	6	1,5,6,7,8,11	0.92	0.63	0.02	1.58
-239.17	5	1,3,5,8,11	0.99	0.61	0.02	1.64
-239.12	6	1,3,5,8,10,11	1.04	0.59	0.02	1.68
-239.11	6	1,2,3,5,8,11	1.05	0.59	0.02	1.69
-239.10	6	1,5,8,9,10,11	1.06	0.59	0.02	1.70
-239.10	7	1,2,3,5,8,10,11	1.06	0.59	0.02	1.70
-239.08	7	1,5,7,8,9,10,11	1.08	0.58	0.02	1.72
-238.97	6	1,5,6,8,9,11	1.19	0.55	0.02	1.81
-238.95	8	1,2,3,5,6,8,10,11	1.21	0.55	0.02	1.83
-238.94	7	1,5,6,7,8,10,11	1.22	0.54	0.02	1.84
-238.91	5	1,5,8,9,11	1.25	0.54	0.02	1.87
-238.91	6	1,5,7,8,9,11	1.25	0.54	0.02	1.87
-238.90	7	1,5,7,8,10,11,12	1.26	0.53	0.02	1.88
-238.88	6	1,5,6,8,11,12	1.28	0.53	0.02	1.90
-238.86	8	1,2,3,5,6,8,11,12	1.30	0.52	0.02	1.92
-238.83	7	1,3,5,6,8,10,11	1.33	0.51	0.02	1.94
-238.80	6	1,5,8,10,11,12	1.36	0.51	0.02	1.97
-238.71	6	5,7,8,9,10,11	1.45	0.48	0.01	2.06
-238.67	7	1,4,5,7,8,10,11	1.49	0.47	0.01	2.11
-238.66	5	5,8,9,10,11	1.50	0.47	0.01	2.12
-238.65	7	1,5,6,8,9,10,11	1.51	0.47	0.01	2.13
-238.63	6	1,5,7,8,11,12	1.53	0.47	0.01	2.15
-238.61	6	5,7,8,10,11,12	1.55	0.46	0.01	2.17
-238.57	8	1,2,3,5,6,8,9,11	1.59	0.45	0.01	2.21
-238.55	6	1,3,5,7,8,11	1.61	0.45	0.01	2.24
-238.55	7	1,5,6,8,10,11,12	1.61	0.45	0.01	2.24
-238.54	5	1,5,8,11,12	1.62	0.44	0.01	2.25
-238.51	7	1,3,5,7,8,10,11	1.65	0.44	0.01	2.28
-238.50	6	1,3,4,5,8,11	1.66	0.44	0.01	2.29
-238.49	6	1,4,5,7,8,11	1.67	0.43	0.01	2.30
-238.47	6	1,4,5,8,10,11	1.69	0.43	0.01	2.33

-238.43	5	2,6,7,8,11	1.73	0.42	0.01	2.38
-238.42	6	1,4,5,6,8,11	1.74	0.42	0.01	2.39
-238.42	7	1,2,3,4,5,8,11	1.74	0.42	0.01	2.39
-238.42	4	5,8,10,11	1.74	0.42	0.01	2.39
-238.42	5	3,6,7,8,11	1.74	0.42	0.01	2.39
-238.41	6	1,2,5,6,8,11	1.75	0.42	0.01	2.40
-238.41	7	1,3,5,6,8,11,12	1.75	0.42	0.01	2.40
-238.38	5	5,8,10,11,12	1.78	0.41	0.01	2.44
-238.35	5	6,7,8,11,12	1.81	0.40	0.01	2.47
-238.32	7	1,3,5,6,8,9,11	1.84	0.40	0.01	2.51
-238.32	6	1,3,5,8,9,11	1.84	0.40	0.01	2.51
-238.31	9	1,2,3,5,6,8,10,11,12	1.85	0.40	0.01	2.52
-238.27	5	5,7,8,10,11	1.89	0.39	0.01	2.57
-238.26	7	1,2,3,5,8,9,11	1.90	0.39	0.01	2.59
-238.24	7	1,2,3,8,11,12	1.92	0.38	0.01	2.61
-238.24	7	1,2,5,7,8,10,11	1.92	0.38	0.01	2.61
-238.24	5	1,6,7,8,11	1.92	0.38	0.01	2.61
-238.23	5	1,4,5,8,11	1.93	0.38	0.01	2.62
-238.22	7	1,2,3,5,7,8,11	1.94	0.38	0.01	2.64
-238.22	8	1,2,3,5,7,8,10,11	1.94	0.38	0.01	2.64
-238.21	5	4,6,7,8,11	1.95	0.38	0.01	2.65
-238.21	5	6,7,8,10,11	1.95	0.38	0.01	2.65
-238.19	8	1,2,3,5,8,10,11,12	1.97	0.37	0.01	2.68
-238.19	7	1,3,5,6,7,8,11	1.97	0.37	0.01	2.68
-238.18	7	1,3,4,5,8,10,11	1.98	0.37	0.01	2.69

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* **Metric Numbers (see Table 3 for explanation of metric abbreviations):** 1. *No species*; 2. *Dominance*; 3. *Sh-div*; 4. *Prop trop spec*; 5. *No trop spec*; 6. *No trop gen*; 7. *Prop detr*; 8. *Prop benthic*; 9. *No benthic*; 10. *Feed guild comp*; 11. *Prop est spawn*; 12. *No est spawn*