Personality profiling may help select better cleaner fish for sea-lice control in salmon farming

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Abstract

Lumpfish (*Cyclopterus lumpus*) are increasingly being used as cleaner fish to control parasitic sea-lice in salmon farming, but cleaning rates are very variable and not all individuals eat sea-lice, which increases the risk of emaciation and has ethical and practical implications. Selecting good cleaners is a priority to make the industry more sustainable, but there is little information on what behaviours make cleaner fish effective under a commercial setting. We examined variation in lumpfish personalities according to the five-factor personality model that takes into account differences in activity, anxiety (shelter use, thigmotaxis), aggression, sociality, and boldness (neophobia). We then quantified how variation in lumpfish personalities influenced interactions with naïve Atlantic salmon (*Salmo salar*), without the confounding effects of variation in sea-lice loads. Variation in activity, sociality, aggression and neophobia, but not in anxiety, was repeatable, which is consistent with a heritable basis. Neophilic, non-aggressive lumpfish spent more time inspecting salmon than neophobic and aggressive individuals, but salmon fled in the presence of the most active and social individuals, suggesting there may be an optimal cleaner fish personality amenable to artificial selection. The personality screening protocols developed in this study could inform a more efficient use of cleaner fish in salmon farming and reduce the number of individuals required to control sea-lice.

2

Introduction

Various species of wrasse and lumpfish (*Cyclopterus lumpus*) are increasingly being used as facultative cleaner fish to remove parasitic sea-lice from farmed salmon (Powell *et al.*, 2018b; Treasurer, 2018a; Treasurer, 2018b). Using facultative cleaner fish for pest control offers many advantages over chemical methods (Powell *et al.*, 2018b), but relies on cleaner fish engaging in parasite removal (delousing) under a commercial setting. However, lumpfish do not generally feed on sea-lice, or act as cleaner fish, in the wild (Davenport, 1985; Powell *et al.*, 2018a), which poses a challenge for optimizing their use in salmon farming. Lumpfish are opportunistic generalist feeders that will graze on sea-lice in salmon cages, especially when alternate food sources are limited (Imsland *et al.*, 2015a; Imsland *et al.*, 2016a). Typically only 13-38% of lumpfish consume sea-lice in salmon cages (Eliasen *et al.*, 2018; Imsland *et al.*, 2015a; Imsland *et al.*, 2014; Imsland *et al.*, 2016b), the majority feed on salmon pellets or graze on plankton (Johannesen *et al.*, 2018), particularly during the summer (Eliasen *et al.*, 2018). This has attracted criticism from regulatory agencies and animal welfare organisations, who point out that many cleaner fish die of malnutrition and suffer from low welfare because they are being used for a task they do not naturally do (European Union Reference Laboratory for Fish Diseases, 2016; Stranden, 2020). A call has been made for the use of cleaner fish to stop until their welfare can be guaranteed and the sources of mortality are addressed (Compassion in World Farming, 2018; OneKind, 2018). There is, therefore, a need to select individuals that readily engage in cleaning behaviour and consume sea-lice, as this would increase delousing rates with fewer cleaner fish, improve welfare, and reduce the risk of emaciation (Gutierrez Rabadan *et al.*, 2020).

66   Lumpfish can be effective cleaners (Imsland *et al.*, 2014; Imsland *et al.*, 2018)

67   and reduce sea-lice loads on salmon by as much as 93% under the right conditions

68   (Imsland *et al.*, 2016b), but seemingly this is because certain individuals do most of

69   the cleaning. Individual variation in cleaning behaviour is common among facultative

70   cleaner fish, and some individuals may attend clients and engage in cleaning, while

71   others ignore them (Morado *et al.*, 2019). Understanding such variation is important

72   because cleaning behaviour appears to be inherited (Imsland *et al.*, 2016b), and the

73   ability to screen individuals with a predisposition for cleaning may facilitate a selective

74   breeding program (Powell *et al.*, 2018b). However, there is a paucity of robust data on

75   individual variation in cleaning behaviour and little information on lumpfish-salmon

76   interactions (Overton *et al.*, 2020), which has so far hampered progress towards the

77   domestication of lumpfish as cleaner fish in aquaculture.

78   Domestication requires animals to adapt to life in captivity (Price, 1999), to

79   express some behaviours and to suppress others (Belyaev, 1969; Jensen, 2014).

80   Juvenile lumpfish aggregate in clumps and are sit and wait feeders (Powell *et al.*,

81   2018a; Powell *et al.*, 2018b). They are also poor swimmers (Hvas *et al.*, 2018), have

82   a low aerobic scope (Killen *et al.*, 2007b), and use their suction cup to attach to shelters

83   to conserve energy (Killen *et al.*, 2007a). They are not well adapted to pursue prey,

84   and do not normally interact with other fish species. To function as cleaner fish,

85   lumpfish may need to overcome the fear of approaching a much larger "client" fish,

86   change their social behaviour, and become more exploratory, active and inquisitive.

87   More specifically, delousing salmon requires lumpfish to take four successive steps:

88   (1) leave the safety of being in a group and/or in a shelter, (2) approach a much larger

89   and faster swimming fish (salmon), (3) identify clients that are infested with sea-lice,

90   and (4) remove sea-lice from the skin of a fast moving target. This sequence of events

91   requires a particular skillset that not all individuals may possess, which might explain

92   why only a small proportion of lumpfish clean parasitic sea-lice in salmon farms. We

93   therefore hypothesized that only those individuals that have a bold personality, show

94   exploratory behaviour, or are more active and willing to take risks may interact with

95   salmon. Identifying those individuals might be possible through personality profiling

96   *sensu* McCann (1992).

97   Personality profiling has been used to understand variation in personalities in

98   humans (Costa Jr & McCrae, 1990; Neal *et al.*, 2012; Van Dijk *et al.*, 2017), but

99   increasingly also in non-humans (Gosling & John, 1999), where it is referred as

100   temperament or stress coping styles (Dingemanse *et al.*, 2010; Piersma & Drent,

101   2003). Personality traits are repeatable in many taxa, including fish (Castanheira *et*

102   *al.*, 2017; Elias *et al.*, 2018; Vargas *et al.*, 2018), which opens possibilities for artificial

103   selection and the domestication of cleaner fish in aquaculture. We therefore tested if

104   personality profiling using the five-factor model of non-human animal personality

105   (Gosling & John, 1999) could be used to identify lumpfish better suited to behave as

106   cleaner fish in salmon farms. We also tested if behaviours relevant to delousing were

107   repeatable, as only repeatable behaviours can be inherited and modified by artificial

108   selection during animal domestication (Belyaev, 1979).

109

Materials and Methods

110

111   We used a four-step approach to assess the effects of lumpfish personality on

112   lumpfish-salmon interactions. We first screened individually tagged lumpfish for five

113   dimensions of animal personality (activity, sociality, anxiety, aggression, and

114   boldness; (Gosling & John, 1999) in the absence of salmon. We then retested fish

115   after ~1 month to assess the repeatability of behaviour along each dimension, and

116   generated personality scores from Principal Component Analysis to account for

117   correlated behaviours. Finally, we examined whether lumpfish personality scores

118   predicted lumpfish-salmon interactions.

119

120   *Source and rearing of experimental fish*

121   Lumpfish eggs were collected from wild adults caught in Iceland and the English

122   Channel during the winter of 2016/2017, representing two genetically distinct

123   populations (Whittaker *et al.*, 2018). Juveniles were reared for one year (mean weight

124   = 114.8 ±9.7 g SE) under recirculation aquaculture conditions and a sample allocated

125   at random to eight 1500L tanks (1.4 m diameter, 0.9 m depth; 33 fish/tank; initial

126   biomass = 75.37 ±30.99 g/m^3) and individually marked with PIT tags (7 x 1.35 mm,

127   Loligo) in March 2017. Water temperature was maintained at 11-13C, salinity at 28-

128   32ppt, and photoperiod at 12D:12L; fish were fed twice per day (Amber Neptune

129   Skretting, UK) at 2% tank biomass, as recommended for the species (Powell *et al.*,

130   2018b).

131

132   *Personality profiling*

133   We filmed 38 individually tagged lumpfish of two origins (Iceland, n = 16; England, n

134   = 22) over four consecutive phases, each lasting 10 minutes, using CCTV (1080p

135   camera, Sannce, Hong Kong). In phase 1 (neutral), a single lumpfish was introduced

136   into one of two white rectangular test arenas (L120 cm x W55 cm x D25 cm) and was

137   left to acclimatise for 10 mins without any additional stimulus. The test arenas were

138   divided into three equal zones using tape to facilitate video analysis, were each fitted

139   with an air stone to maintain dissolved oxygen at 100% saturation and were

140   surrounded by a black tarpaulin screen to minimise disruption. In phase 2 (shelter) a

6

141 black smooth PVC panel was introduced to one end of the test arena to provide a

142 refuge, as lumpfish seek smooth, dark substrates (Imsland *et al.*, 2015b). In phase 3

143 (mirror), a mirror was added to the arena, opposite to the shelter. Finally, in phase 4

144 (novel), a novel object was placed at the centre of the arena (**Figure 1**), a yellow golf

145 ball in the first trial and a green Lego brick in the second repeat to prevent habituation.

146 The four screening phases were conducted in the same order for every fish. Water

147 was replaced between fish to avoid a build-up of stress hormones.

148 Behaviours were scored from video recordings using BORIS version 7.75

149 (Friard & Gamba, 2016) by one person who did not have knowledge of the identity of

150 the fish or the trial conditions. We examined two metrics of activity in phase 1 (neutral):

151 crossing speed across the central portion of the test arena (cm/s), and number of

152 crosses between the three arena sections. We also measured activity by recording the

153 total time spent swimming (s) throughout all four phases. Anxiety was assessed by

154 recording the total time spent within 10cm of the tank walls (thigmotaxis) during phase

155 1 (neutral) and also the total time spent within 10cm of the black panel in phase 2

156 (shelter), as both are established methods of assessing anxiety in fish (Cianca *et al.*,

157 2013; Godwin *et al.*, 2012). To score aggression, we counted the number of agonistic

158 actions (nips and charges) directed towards the mirror image (Rodriguez-Barreto *et*

159 *al.*, 2019) during phase 3 (mirror). The number of approaches to the mirror that did not

160 result in body contact, as well as the time spent within close proximity (<10 cm) of the

161 mirror during this phase were used as measures of sociality (Cattelan *et al.*, 2017). As

162 a measure of boldness, we counted the number of times individuals were within 10 cm

163 of the novel object phase 4 (novel), the time latency to first approach the novel object,

164 and average distance (cm) from novel object at one minute intervals, as these are

165 measures of neophobia that map well into the boldness-shyness continuum

166   (Champneys *et al.*, 2018). Collectively, these metrics capture variation in five

167   dimensions of fish personality and have been associated with the expression of

168   particular genes in the fish brain (Champneys *et al.*, 2018; Rodriguez-Barreto *et al.*,

169   2019). We also measured body mass (g) and calculated specific growth rate

170   (SGR%,(Lugert *et al.*, 2016) between the first and second repeated trials to account

171   for the influence of feeding motivation on behaviour.

172

173   *Quantifying lumpfish-salmon interactions*

174   Atlantic salmon (*Salmo salar*) post-smolts (n = 20, mean mass = 175.6 ± 37.6g SE)

175   were obtained from a commercial farm in Scotland in July 2017 and quarantined for

176   one month in two 1500 litre recirculating aquaculture tanks (1.4m diameter, 0.9m

177   depth), at a density of 10 salmon per tank (initial biomass = 117.04 ±25.06 g/m^3 SE).

178   In August 2017, the same tagged lumpfish that had previously been screened for

179   personality traits (n = 38) were introduced singly into one of the two salmon tanks and

180   recorded via CCTV for 20 minutes each. An ethogram based on previous studies on

181   cleaner fish (Bshary & Côté, 2008; Horton, 2011) was constructed from the following

182   three behaviours: time spent visually assessing salmon, often from multiple angles

183   ("inspection, s"), time spent following salmon ("pursuit, s"), and number of times

184   salmon fled when they were approached by lumpfish ("flee", no/min). Salmon were

185   free of sea-lice to ensure that interactions with lumpfish were unaffected by variation

186   in sea-lice loads, thereby ensuring consistency between replicated trials and between

187   individuals. This would not have been possible if sea-lice loads had decreased as a

188   result of lumpfish delousing, as this might have changed the behaviour of both species.

189   All lumpfish were naive to salmon and salmon were also naive to lumpfish initially, but

190   they were exposed to multiple lumpfish over the course of the study.

Repeatability of behaviours

191   R version 4.0. (R Core Team, 2020) was used for all statistical analyses. To asses the

193   repeatability (*R*) of behaviours we used mixed models to identify significant

194   behavioural covariates using the *lme4* package (Bates *et al.*, 2014). We employed

195   linear mixed models (LMM) in the case of continuous behavioural metrics (e.g.

196   duration of events, swimming speed and distance to novel object), and generalized

197   linear mixed-models (GLMM) in the case of frequency of events (e.g. number of

198   crosses across the test arena, and approaches to the mirror or the novel object). We

199   included sex, stock origin (Iceland, England), specific growth rate (SGR, %), and time

200   of filming (days elapsed) as fixed factors, and test tank, home tank, and fish ID as

201   random factors to account for repeated sampling and to control for grouping and

202   potential non-independence of results. For each behavioural metric we identified

203   minimal adequate models (Crawley, 2013) based on changes on AICc using the

204   *dredge* function in the *MuMIn* package (Barton & Barton, 2015), and used the *anova*

205   command and the Likelihood-Ratio Test (LRT) to compare these to null models without

206   predictors. Model assumptions were checked by inspection of diagnostic plots with

207   *sjPlot* (Lüdecke, 2020), and if these were not met, the significance of results was

208   compared with robust estimates using the *robustlmm* package (Koller, 2016). The

209   most plausible models were refitted by Restricted Maximum Likelihood (REML) to

210   derive corrected probability values.

211   We used the *rptR* package (Stoffel *et al.*, 2017) to calculate adjusted

212   repeatabilities (*R*; (Nakagawa & Schielzeth, 2010; Schuster *et al.*, 2017), using fish ID

213   (n = 38) and repeat (n = 2) as grouping variables, and any significant covariates

214   identified above; 95% confidence intervals were calculated via 1,000 bootstraps, using

215   a gaussian or a poison link, depending on the nature of the response variables.

216   Behaviour was considered repeatable if the lower 95% CI exceeded zero (Neumann

217   *et al.*, 2013) and repeatability was deemed low ($R < 0.2$), moderate ($R = 0.2$-0.4), or

218   strong ($R > 0.4$), as in other studies of animal personalities (Bohn *et al.*, 2017). Non-

219   repeatable behaviours were excluded from analysis and repeatable behaviours were

220   averaged to obtain a single value per fish.

221

222   *Personality scores and effects on lumpfish-salmon interactions*

223   Four repeatable behaviours identified from the personality profiling (crossing

224   frequency, approaches to mirror, charges at mirror, and approaches to novel object

225   were converted to frequency rates (No/min) and used to generate personality scores

226   via Principal Component Analysis to account for correlated behaviours and lack of

227   independence (Gosling & John, 1999; Wilson *et al.*, 2014). PC scores were rescaled

228   from 0 to 1 using the *scales* package (Wickham *et al.*, 2020) to facilitate comparisons

229   and ensure equal weighting. To examine the effect of personality on lumpfish-salmon

230   interactions we modelled the time lumpfish spent inspecting and pursuing salmon, as

231   well as the salmon fleeing rate, as a function of lumpfish personality scores while

232   statistically controlling for tank effects, stock origin, sex, growth rate, and time elapsing

233   (to account for the cumulative exposure of salmon to lumpfish). We modelled each

234   interaction separately via univariate LMMs and also together via MANOVA, and

235   derived minimal adequate models via model simplification as described above for the

236   repeatability study.

237

238   *Ethics declaration and approval for animal experiments*

239   This study adhered to the ARRIVE guidelines. All experimental procedures were

240   approved by Swansea University, Animal Welfare Review Body, permit IP1617-27.

Results

Repeatability of behaviours

Crossing frequency was influenced by sex (parameter estimate (male) = 0.594 ±0.222, z = 2.675, P = 0.007) and specific growth rate (parameter estimate = 0.525 ±0.195, z = 2.688, P = 0.007), as females and faster growing fish were more active and crossed the test arena more frequently. Aggression decreased the second time the fish were tested against their mirror image (parameter estimate day = -0.010, ±0.004, z = -2.352, P = 0.019), as did the frequency of non-aggressive mirror interactions (parameter estimate day = -0.005 ± 0.001, z = -3.783, P < 0.001). Stock origin influenced the time individuals spent close to the tank perimeter (parameter estimate (UK) = 56.18 ± 22.72, t_{74} =2.473, P = 0.016) and the number of approaches made to novel objects (parameter estimate (UK) = -1.611 ± 0.386, z =-4.171, P < 0.001), with fish from the English Channel spending more time close to the walls and making fewer interactions with the novel object than fish from Icelandic origin. We therefore included sex and specific growth rate to estimate the adjusted repeatability of crossing frequency, geographic origin to estimate the repeatability of time spent close to the walls and frequency of encounters with the novel object, and time between trials to estimate the repeatability of interactions with the mirror image.

Of the 11 behaviours considered, 4 were repeatable corresponding to the activity, aggression, sociality and boldness dimensions of animal personality (**Table 1**). Crossing speed and time spent swimming were strongly repeatable (R>0.4), crossing frequency and frequency of interactions with the mirror and the novel object were moderately repeatable (R = 0.2-0.4), while aggression had a low repeatability

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265   (R = 0.184). Distance to the novel object and the two measures of anxiety were not

266   repeatable.

267

268   *Personality scores*

269   Significant positive correlations were found between two of the four repeatable

270   behaviours (**Table 2**). Activity was positively correlated with sociality, and sociality

271   was positively correlated with aggression. The first two principal components

272   accounted for 68% of the variation in personality. PC1 was mostly driven by sociality

273   (loading = -0.64) and activity (loading = -0.58), while PC2 mostly measured boldness

274   (loading = +0.94) against aggression (loading = -0.26). PC3 was not significant in

275   any of the models considered.

276

277   *Lumpfish-salmon interactions*

278   In the presence of salmon, most lumpfish engaged in visual inspections (89% of

279   cases) and triggered one or more flight responses from salmon (89% of cases), but

280   only 34% of lumpfish pursued salmon (**Figure 2)**. Lumpfish that spent more time

281   inspecting salmon were also more likely to pursue them (Spearman rho = 0.550, df =

282   37, *P* < 0.001). Time spent pursuing salmon was not explained by personality ($F_{7,30}$

283   = 1.066, *P* = 0.408) but lumpfish personality predicted the time spent inspecting

284   salmon (PC2 estimate = -18.151 ± 8.861, $t_{34.385}$ = -2.048, *P* = 0.048), as well as the

285   frequency of salmon flights (PC1 estimate = -1.005 ± 0.242, $t_{33.419}$ = -4.150, *P* <

286   0.001) while statistically controlling for significant random tank effects. Individuals

287   that were not afraid of the novel object during the initial behavioural profiling

288   (neophilic) subsequently spent more time inspecting salmon than neophobic fish, as

289   did the least aggressive lumpfish (PC2 - **Figure 3A**). Salmon were more likely to

290   flee in the presence of the most active and social individuals (PC1 - **Figure 3B**).

291   MANOVA indicated that lumpfish-salmon interactions were predicted by

292   personality (PC1 Pillai = 0.422, $F_{3,33}$= 8.047, $P < 0.001$) and growth rate (Pillai =

293   0.332, $F_{3,33}$= 5.480, P =0.004), and provided a significantly better fit than a null

294   model ($F_{6,68}$= 5.398, $P < 0.001$).

295

Discussion

Our study shows that personality profiling can be used to predict how lumpfish interact with salmon and, possibly, whether they will make good cleaner fish. In particular, we show that bold, neophilic lumpfish were more likely to inspect salmon, while the most active and social individuals were more likely to cause salmon to flee. As these behaviours were repeatable, and therefore likely heritable (Dohm, 2002; Lynch & Walsh, 1998), this suggests that artificial selection could be used to select better cleaner fish through domestication (Powell *et al.*, 2018b). This is consistent with results that show that delousing behaviour is parentally controlled (Imsland *et al.*, 2016b) and thus likely inherited. However, of the 37% of lumpfish that pursued salmon in our study, only 5% did so without causing salmon to flee. The challenge for domesticating lumpfish as cleaner fish, hence, might be how to select individuals that are bold enough to approach salmon in search of sea-lice, but not so aggressively as to cause salmon to flee.

The distribution of lumpfish-salmon interactions was highly skewed. The majority of lumpfish had limited interactions with salmon, but a few individuals interacted much more than the rest. For example, 7 individuals accounted for 60% of all the inspections, and just three individuals accounted for 60% of all the pursuits (Figure 2) with only 37% of them pursuing salmon. This is consistent with results from diet analysis that indicate that only ~30% of lumpfish consume sea-lice in salmon cages (Eliasen *et al.*, 2018; Imsland *et al.*, 2015a; Imsland *et al.*, 2014; Imsland *et al.*, 2016b), which our results suggest might be due to variation in animal personalities.

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320 Boldness is a significant predictor of interactions in dedicated cleaner fish (Dunkley

321 *et al.*, 2019; Wilson *et al.*, 2014), and it was repeatable in our study, suggesting it

322 could targeted by artificial selection. Likewise, activity, exploratory behaviour and

323 aggression were also repeatable, and several studies have shown that these traits

324 are inherited in several fish species (Ariyomo *et al.*, 2013; Bakker, 1986; Chervet *et*

325 *al.*, 2011; Magnhagen, 2012; Sutrisno *et al.*, 2011).

326

327 Breeding programs could establish pedigree lines from lumpfish families with proven

328 delousing ability in sea-cages (Imsland *et al.*, 2016b) and select for stocks with

329 desirable behaviours. For example, fish from Icelandic origin in our study spent

330 significantly more time interacting with the novel object than fish from the English

331 Channel, suggesting there may be genetic differences in risk-taking behaviour that

332 could be improved through selective breeding. There is no information on the

333 heritability of any behavioural traits in lumpfish, but the estimated repeatabilities for

334 swimming duration (R = 0.422) and frequency of approaches to the novel object (R =

335 0.340) could be used as upper values for narrow sense heritability (h^2) of pursuing

336 and inspection behaviours, respectively (Dohm, 2002; Lynch & Walsh, 1998). Using

337 these values to estimate the response to artificial selection suggests that selecting

338 the top 10% most active and boldest lumpfish for breeding could increase the time

339 lumpfish spend inspecting and pursuing salmon 1.4-3.5 times within one generation,

340 respectively. In this sense, protocols could be developed to screen lumpfish

341 personalities in hatcheries, and exclude from subsequent rearing and deployment

342 those individuals less likely to approach salmon. Currently, many lumpfish do not

343 engage in cleaning behaviour, and selecting for behaviours that make good cleaners

344   could drastically reduce the number of lumpfish required on farms, reducing costs

345   and improving welfare (Garcia de Leaniz *et al.*, 2021).

346

347   The selection of "elite" lines of cleaner fish that are particularly bold and active, but

348   not overly aggressive, could be done in different ways. For example, one way

349   boldness could be selected is by targeting lumpfish with high metabolic rate (Hvas *et*

350   *al.*, 2018) and low cortisol response (Gutierrez Rabadan *et al.*, 2021), or more

351   efficiently, by targeting genes associated with boldness and aggression (Rodriguez-

352   Barreto *et al.*, 2019). Metabolic rate can be used to predict boldness in some fish

353   species (Killen *et al.*, 2012) and can also be used to predict foraging mode (active vs

354   passive) in lumpfish (Killen *et al.*, 2007a). This is important, as presumably only

355   active lumpfish that swim to pursue their prey (as opposite to passively foraging

356   while clinging) will make efficient cleaners.

357

358   One reason why some farmed lumpfish do not survive the salmon production cycle

359   in sea cages is because they fail to feed and adapt to a novel environment (Imsland

360   *et al.*, 2020; Imsland *et al.*, 2019b). Failure of hatchery-reared lumpfish to adapt to

361   the sea-cage environment could be due to phenotypic mismatch, as seen in other

362   species (Stringwell *et al.*, 2014), but steps can be taken to reduce maladaptation.

363   Fish personality is shaped by both intrinsic and extrinsic drivers (Brown *et al.*, 2011),

364   most notably through early experience (Dingemanse *et al.*, 2009; Huntingford &

365   Garcia Garcia de Leaniz, 1997), and one way maladaptation could be reduced is by

366   manipulating the rearing environment through environmental and social enrichment.

367   Environmental enrichment can modify risk-taking behaviours in fish very rapidly

368   (Roberts *et al.*, 2011; Roberts *et al.*, 2014) and this could perhaps be used to

369 suppress fear and enhance cleaning behaviour in lumpfish. For example, feeding

370 sea-lice and live prey to lumpfish prior to cage deployment was found to promote

371 subsequent delousing behaviour (Imsland *et al.*, 2019a), and previous exposure to

372 salmon may also reduce stress and improve cohabitation (Staven *et al.*, 2019). In

373 general, intensive fish farming seems to modify fish behaviours in predictable ways,

374 by altering patterns of gene expression in the fish brain that can be targeted by

375 selective breeding (Rodriguez-Barreto *et al.*, 2019). Social enrichment prior to

376 deployment in sea cages could be used to modify behaviours and facilitate

377 adaptation of lumpfish to sea cages. For example, living in socially impoverished

378 habitats decreases cleaning efficacy in wrasse (Wismer *et al.*, 2014), and the same

379 could happen in lumpfish.

380

381 Cleaning behaviour could also be improved through size selection and manipulation

382 of growth rate. We found that faster growing lumpfish interacted more with salmon

383 than slower growing fish, suggesting that selecting for fast growing lumpfish might

384 also select for more active, bolder lumpfish which might perform better as cleaner

385 fish. Lumpfish hatcheries typically supply relatively small juveniles to sea-cages

386 (approx. 20g), as this is thought to be an optimal size for cleaning behaviour

387 (Imsland *et al.*, 2016c). However, more recent studies indicate that body size

388 accounts for little variation in delousing rates, and that smaller lumpfish are more

389 likely to have empty stomachs (Eliasen *et al.*, 2018). Larger cleaner wrasse also

390 interact more with salmon (Whittaker *et al.*, 2021) and a re-assessment of the

391 optimal size for lumpfish deployment warrants further study.

392

393   In summary, our results indicate that only a small proportion of lumpfish interact with

394   salmon in ways that are conductive to cleaning behaviour. As some personality traits

395   were found to be repeatable, this opens the possibility for artificially selecting cleaner

396   fish with desired behaviours, a process that our study suggests could be rapid.

397   Failure to feed on sea-lice is a major cause of emaciation and mortality among

398   lumpfish used as cleaner in salmon farming (Gutierrez Rabadan *et al.*, 2021), and

399   behavioural profiling could be used to select better cleaner fish and make the

400   industry more sustainable. Further studies, using pedigree analysis of variation in

401   delousing rates could be used to estimate the heritability of personality traits and

402   their association with sea-lice removal.

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413   **Data availability**

414   The data files for this study have been deposited in figshare

415   https://doi.org/10.6084/m9.figshare.14626839.v1

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660

661

662 **Table 1.** Repeatability (R) of behaviours used to generate personality scores for

663 lumpfish. Repeatable behaviours are highlighted in bold.

664

Personality component	Behaviour	R	SE	*P*
Activity	**Crossing speed (cm/s)**	**0.651**	**0.097**	**<0.001**
	Crossing frequency (No.)	**0.278**	**0.127**	**0.018**
	Swimming duration (s)	**0.422**	**0.135**	**0.004**
Sociality	**Approaches to mirror (No.)**	**0.375**	**0.118**	**<0.001**
	Time close to mirror (s)	0.000	0.080	1.000
Anxiety	Time in arena perimeter (s)	0.000	0.094	1.000
	Time in shelter (s)	0.177	0.135	0.124
Aggression	**Charges at mirror (No.)**	**0.184**	**0.238**	**0.005**
Boldness	**Approaches to novel object (No.)**	**0.340**	**0.186**	**0.033**
	Latency to novel object (s)	0.184	0.137	0.163
	Distance to novel object (cm)	0.226	0.139	0.092

665

666   **Table 2.** Correlation matrix between repeatable behaviours in lumpfish used to

667   generate personality scores via Principal Component Analysis. Upper diagonal

668   displays the Pearson's correlation coefficient and lower diagonal the associated

669   probabilities. Significant correlations are highlighted in bold.

670

Personality component	Activity	Sociality	Aggression	Boldness
Activity (No. crosses/min)		**+0.440**	+0.210	-0.046
Sociality (No. mirror approaches/min)	*0.006*		**+0.330**	+0.098
Aggression (No. mirror charges/min)	*0.210*	*0.044*		-0.094
Boldness (No. novel object approaches/min)	*0.780*	*0.560*	*0.580*	

671

672

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674

675

676 **Figure 1.** Experimental design showing the four experimental phases, each lasting

677 10 minutes to asses variation in lumpfish personalities. In the neutral phase (phase

678 1), a perimeter was superimposed over the video footage to assess time spent near

679 the walls (thigmotaxis) in an open field test and three equal sections were marked to

680 measure crossing frequency and swimming speed. In the shelter phase (phase 2),

681 the time spent within 10 cm of a black panel was recorded. In the mirror phase

682 (phase 3), the time and frequency of agonistic and non-agonistic approaches to the

683 mirror were recorded. In the novel phase (phase 4), the latency, frequency of

684 approaches within 10 cm and distance to the novel object were recorded.

685

686 **Figure 2**. Interactions observed between single lumpfish and 10 post-salmon smolts

687 during 20-minute observation sessions (n = 38). Dotted line shows the mean number

688 of interactions across all observations.

689

690 **Figure 3.** Relationship between significant lumpfish personality scores (PC1, PC2)

691 derived from behavioural profiling and (A) time spent by lumpfish inspecting salmon,

692 and (B) frequency of salmon flights in response to lumpfish approaches.

693

694

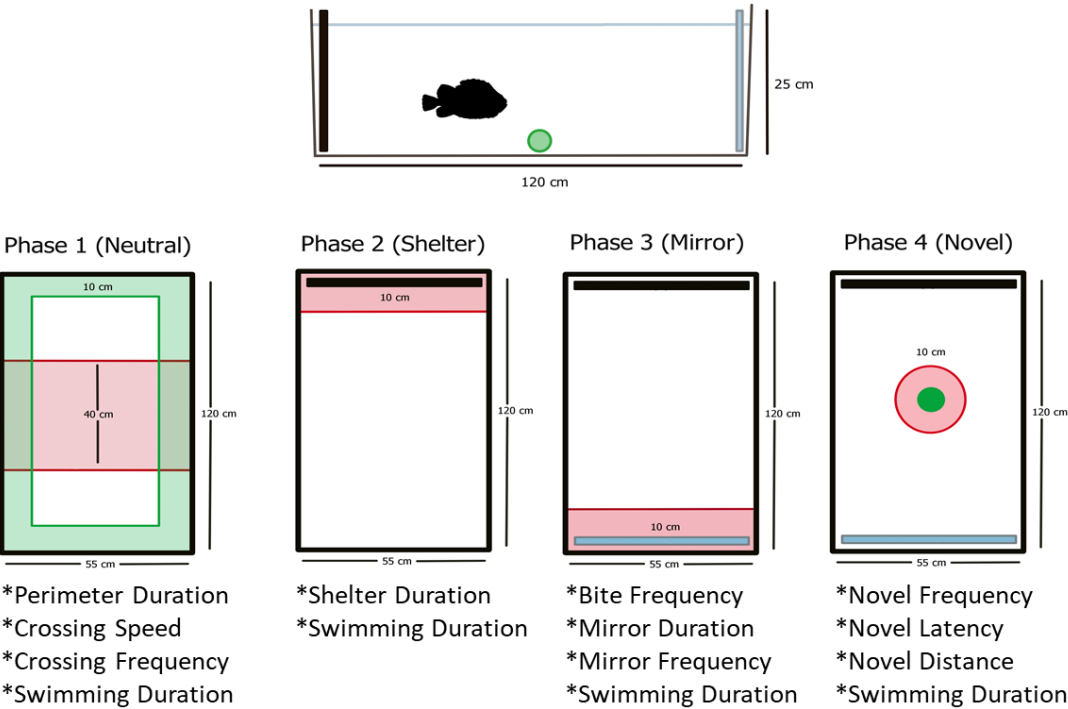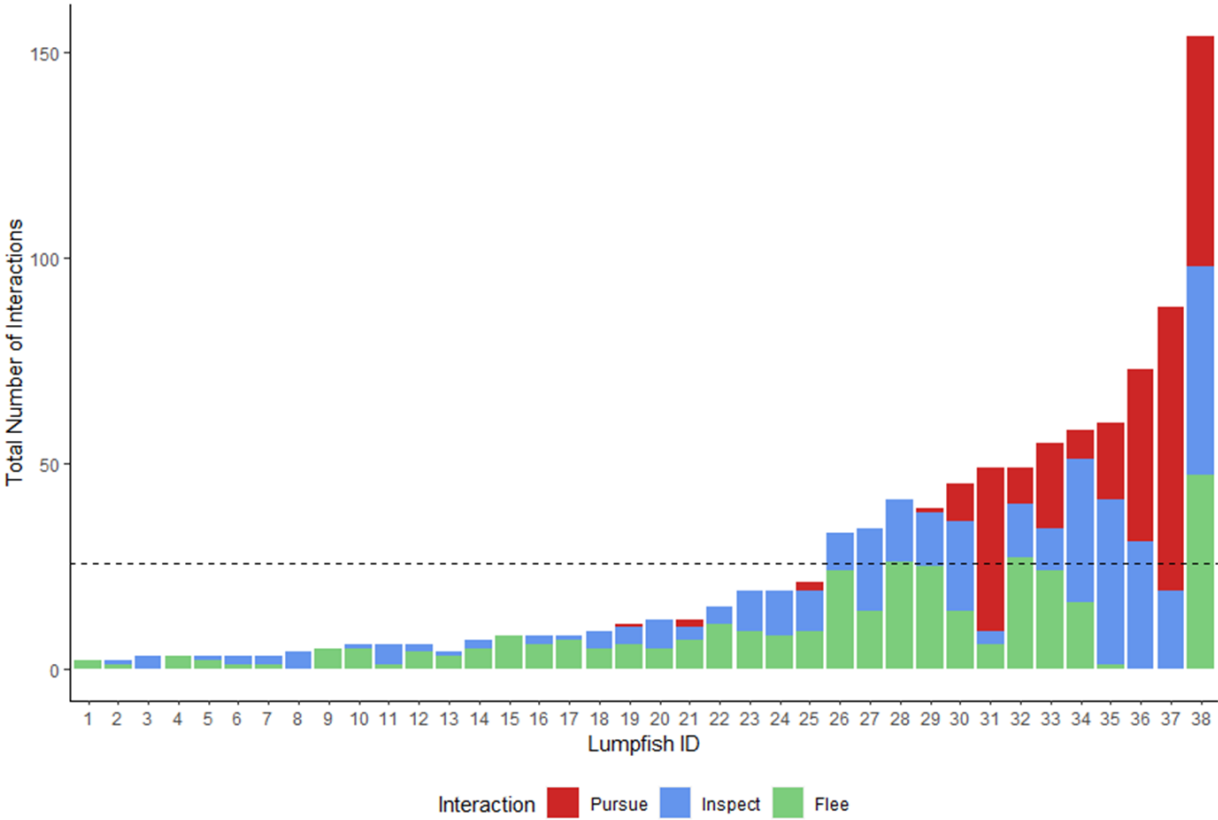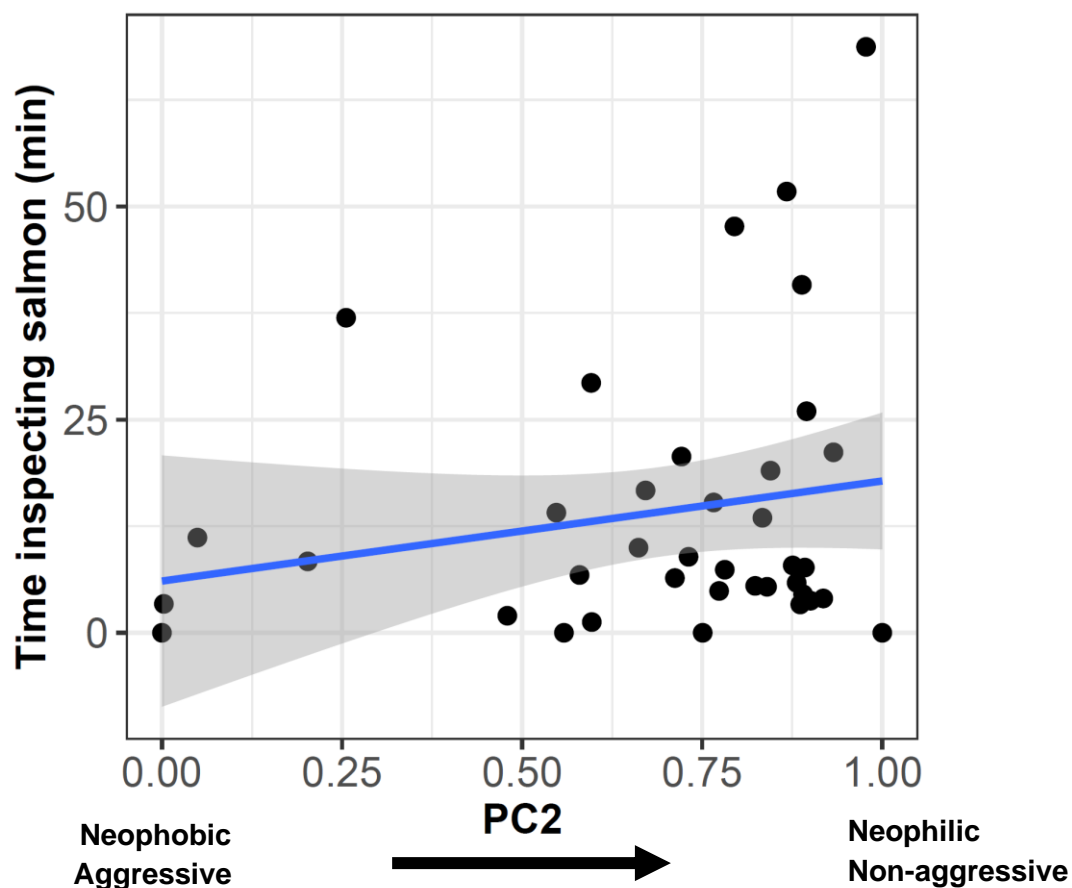695   **Figure 1**

696

Phase 1 (Neutral)
*Perimeter Duration
*Crossing Speed
*Crossing Frequency
*Swimming Duration

Phase 2 (Shelter)
*Shelter Duration
*Swimming Duration

Phase 3 (Mirror)
*Bite Frequency
*Mirror Duration
*Mirror Frequency
*Swimming Duration

Phase 4 (Novel)
*Novel Frequency
*Novel Latency
*Novel Distance
*Swimming Duration

697 **Figure 2**

698

699

700

701

Figure 3

(A)

Neophobic
Aggressive

Neophilic
Non-aggressive

(B)

Sedentary
Non-social

Active
Social

34