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1 **Energy allocation trade-offs between life-history traits**
2 **in the Mediterranean sardine: an ecophysiological**
3 **approach**
4

5 Beauvieux Anaïs^{1*}, Queiros Quentin^{1,2}, Metral Luisa¹, Dutto Gilbert¹ Gasset Eric¹, Criscuolo
6 François³, Fromentin Jean-Marc¹, Saraux Claire^{1,3} & Schull Quentin.¹

7 ¹MARBEC, Univ Montpellier, Ifremer, IRD, CNRS, 34200 Sète, France

8 ²DECOD, INRAE, Institut Agro, IFREMER, 35000 Rennes, France

9 ³IPHC-CNRS & Université De Strasbourg, 67200 Strasbourg, France

10

11

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* Corresponding author : anais.beauvieux@umontpellier.fr

14 **Abstract**

15 Since 2008, the oldest and largest sardines have been disappearing in the Gulf of Lions which
16 strongly affected the regional fisheries. A bottom-up process involving a shift in their diet
17 towards smaller planktonic preys has been suggested as the main driver affecting their
18 decreasing condition. Yet, their reproductive capacities have not been altered, suggesting
19 potential modifications in energy allocation trade-offs. Whether this could also affect
20 maintenance, in particular at the end of the winter reproductive period, and explain the lower
21 adult survival and the disappearance of older individuals remains unclear. We therefore
22 experimentally investigated the consequences of a seasonal modulation of food availability
23 (summer *vs* winter) on sardine life-history traits and energy allocation trade-offs at the individual
24 and population levels. Our results indicate that food resources during summer had a major effect
25 on energy reserves and growth, limiting the maximum size and body condition reached at the end
26 of reproduction. In addition, food restrictions during growth and/or reproduction periods led into
27 physiological costs mediated by increased oxidative damages. Mediterranean sardines did not
28 show any abilities to do compensatory growth and did not appear to be 'capital
29 breeders'. Instead, they displayed differences in individual qualities in dealing with physiological
30 constraints and displayed various life history strategies regardless of the food modulation. We
31 therefore highlighted three main individual energy allocation strategies: (i) favor body condition,
32 (ii) favor growth or (iii) allocate simultaneously in reproduction and growth. Such understanding
33 is key as climate change is expected to favour phytoplankton of smaller size which might
34 amplify the decrease in condition in Mediterranean sardines.

35 **Keywords:** compensatory growth, capital breeders, individual quality, oxidative stress,
36 reproduction, maintenance, *Sardina pilchardus*

37 **1. Introduction**

38 How organisms acquire, store and use energy or nutrients throughout their annual cycle is a key
39 component of their life strategy and an important feature defining their fitness (McEwen &
40 Wingfield 2003). If/when resources become limiting (in quantity and/or quality), allocating
41 energy to one specific function will occur at the expense of another (Gadgil and Bossert 1970,
42 Zera, Anthony and Harshman 2001), which implies trade-offs between the organism growth,
43 somatic maintenance and reproduction (Stearns 1989).

44 In the natural environment, the availability of resources is variable in time and/or space. As such,
45 animals have evolved a range of strategies to face alternation of high and low resource's levels.
46 For instance, under low resources, growth is often slowed down if not stopped (Sumpter et al.
47 1991). However, some organisms are able to offset and catch up to the predicted size when
48 resources subsequently improve via the so-called "compensatory growth" (Metcalf &
49 Monaghan 2001, 2003, Mangel & Munch 2005). This accelerated growth period has been
50 observed across a wide range of taxa (Albon et al. 1987, Näslund et al. 2015, Stier et al. 2015)
51 and seems to occur following a period of undernourishment rather than malnutrition (Boersma &
52 Wit 1997).

53 To further cope with environmental constraints in resource availability, particularly during
54 breeding, two main and opposite reproductive strategies have been proposed: capital breeding
55 (organisms who store energy by anticipation before reproduction) vs. income breeding (no
56 anticipation, energy intake occurs during the reproductive period) (Stearns 1989). Income

57 breeding aims to reproduce while resources are abundant, leading to a rapid transfer of
58 productivity from the ecosystem to species reproduction. On the opposite, to face the highly
59 energy demanding period of gamete production and offspring raising, some species mostly rely
60 on reserves previously accumulated as, mainly, body fat reserves (Rijnsdorp et al. 2005, Palstra
61 & van den Thillart 2010). This is referred to as “capital breeding”. Although easily described as
62 dichotomous, it is widely acknowledged that breeding patterns are not limited to extreme forms
63 and should be distributed along a range – perhaps a complete continuum – of intermediate types
64 (Stearns 1989).

65 [Such growth and reproductive energy allocation patterns have evolved](#) enable individuals to
66 match their energy expenditure with resource availability and maximise their fitness. Yet, how
67 this could affect trade-offs with other functions, especially regarding the potential costs of body
68 maintenance, is an important question. For instance, the oxidative balance (i.e. balance between
69 production of reactive oxygen species (ROS) owing to metabolism and the level of endogenous
70 and exogenous antioxidant defences) plays a recognized role in the deterioration of body
71 functions and has been proposed as one of the mechanistic bases of ageing (Speakman 2005,
72 Metcalfe & Alonso-Alvarez 2010). However, generality or simplicity of this link within
73 mammals or among taxa is not that evident (Vágási et al. 2019, Kramer et al. 2021). Here, we
74 propose that the current study will test for oxidative stress consequences of manipulated trade-
75 offs in European sardines of the NW Mediterranean Sea.

76 While energy allocation trade-offs and the underlying mechanisms are increasingly studied on
77 terrestrial species (Bonnet et al. 2002, Vedder & Bouwhuis 2018), they are much rarer on marine
78 ones where it is particularly difficult to track individuals in the wild over time. Yet, such trade-
79 offs should be exacerbated in most marine species (at least in fish), which maintain a continuous

80 growth throughout their lives, extending the question of trade-offs from the single somatic
81 maintenance vs. reproduction. Moreover fitness generally increases with size, which should put
82 significant selection pressure on growth and thus urge individuals to grow fast, again leading to
83 possibly exacerbated trade-offs.

84 Often characterized by short lifespan (2 to 7 years) and high reproductive rate, small pelagic fish
85 are key components of marine ecosystems, playing an important role in energetic transfers from
86 lower trophic levels (plankton) to higher ones (*e.g.* humans, tuna, cetaceans, birds, Cury 2000,
87 Frederiksen et al. 2006, Straley et al. 2018). Their population dynamics are known to be greatly
88 affected by environmental fluctuations (bottom-up effects) and predator abundance/human
89 induced changes (top-down effects), causing populations to commonly face variations in
90 abundance (Checkley et al. 2017). Recently, significant changes in life history traits have been
91 observed in the small pelagic fish populations of the Gulf of Lions in the north-western
92 Mediterranean Sea (Saraux et al. 2019). Since 2008, the two dominant small pelagic fish species,
93 *i.e.* sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*), have shown a drastic
94 decrease in size and body condition (Van Beveren et al. 2014). This results in lower value on the
95 stalls, which in return has led to the lowest historical landings of small pelagic fish for 150 years
96 and a local fisheries crisis (Van Beveren et al. 2016a). The hypotheses of a top-down control
97 (overfishing, predation) or epizootic diseases have been recently refuted (Van Beveren et al.
98 2016b, 2017, Queiros et al. 2018), so that the main hypothesis to explain those changes is a
99 bottom-up control, *i.e.* a modification of either size and/or quantity of sardine and anchovy preys
100 (essentially copepods), thus limiting fish energy resources (Brosset et al. 2016a, Saraux et al.
101 2019). Moreover competition for food with other species such as sprat is possible but remain

102 unclear (Pethybridge et al. 2014) and could have changed over the last decade (Brosset et al.
103 2016a).

104 Under limited energy resources, the question of how small pelagic fish, especially sardine which
105 was much more impacted than anchovy (Saraux et al. 2019), solve energy allocation trade-offs
106 might be central in understanding the changes observed at the population level. Indeed, the
107 smaller size of sardines has been shown to result from both a slower growth and from the
108 disappearance of older sardines. On the opposite, a recent study conducted on wild populations
109 showed that sardines started reproducing at smaller sizes and maintained high investment in
110 gonads (Brosset et al. 2016a), suggesting a trade-off between growth and reproduction. Besides,
111 whether the decrease in sardine longevity might result from lower energy resources and/or costs
112 associated with growth and reproduction is still an open question. Sardines are usually
113 considered as capital breeders *i.e.* they store energy in spring and summer that can be mobilized
114 later for the reproduction in winter (Ganias 2009). Depleted reserves at the end of the
115 reproductive period might thus not be enough anymore to support maintenance costs in winter
116 when resources are low.

117 To formally test the hypothesis of change in energy allocation trade-offs in sardines, we
118 experimentally investigated the consequences of a temporal modulation of food resources during
119 two seasons (summer and winter) on life-history traits. Manipulating food size and quantity has
120 previously done by Queiros et al. (2019), our aim was to answer the following three main
121 questions: (i) When feeding conditions improve, do sardines show compensatory growth? We
122 predicted sardines facing poor feeding conditions in summer and then improved conditions in
123 winter to exhibit compensatory body size growth (Mangel & Munch 2005) (ii) How plastic are
124 sardines in terms of reproductive investment? Do they depend exclusively on their stored

125 energy? We tested the hypothesis considering sardines as a capital breeder. In such situation,
126 feeding conditions prior to reproduction (i.e. in summer) will have a major effect, and therefore
127 individuals poorly fed in summer but well fed in winter should not be favoured in regard to
128 sardines poorly fed throughout the entire experiment ; (iii) What are the costs in terms of
129 maintenance of such growth and reproductive energy allocation strategies? If sardines exhibit
130 compensatory growth or higher reproductive investment, we supposed that it should lead to the
131 accumulation of damage at the cellular level (Metcalf & Monaghan 2001) and higher oxidative
132 stress (Mangel & Munch 2005).

133 An extra layer of complexity is added when considering inter-individual differences. Individual
134 heterogeneity within the same population can be observed especially when the environmental
135 conditions are fluctuating or unstable (McNamara 1998, Tuljapurkar et al. 2009). There is indeed
136 a continuum of life history strategies both inter- and intra-specific, with some individuals
137 favouring survival over reproduction and *vice versa* (Reid et al. 2010). In this case, negative
138 correlations between traits should arise, an increase in one trait being conditioned by a decrease
139 in another one. By contrast, if strong heterogeneity in terms of individual quality exists and some
140 individuals of “higher quality” better succeed at facing food limitation, positive correlations
141 among the different life history traits would be expected (*e.g.* some individuals should be able to
142 invest simultaneously in reproduction and growth, Marchand and Boisclair 1998, Wilson and
143 Nussey 2010, Bergeron et al. 2011). We investigated those hypotheses by (i) analysing the inter-
144 individual variance in size and body condition over the different periods of the experiment and
145 (ii) assessing the existence of different strategies or qualities at the end of winter and testing for
146 associated costs through their oxidative status.

147 **2. Material and Methods**

148 **2.1. Experimental design**

149 This study aims to investigate energy allocation trade-offs and individual strategies of sardines in
150 the Gulf of Lions in response to energy limitations imposed during two very distinct periods of
151 their life cycle: summer, with high growth rate due to higher water temperatures and planktonic
152 production peak vs winter, when reproduction takes place. To do so, an 8-month experimental
153 approach on wild adult sardines acclimatized in tanks (detailed below) was carried out
154 considering the food size and quantity during two periods (summer and winter). Both size and
155 quantity of food were taken into account, as a previous study revealed that sardines feeding on
156 small particles (0.1mm, actually ranging between 80 and 250 μm) had to consume twice as much
157 as those feeding on large ones (1.2mm, ranging between 900 and 1500 μm) to achieve the same
158 body condition and growth (Queiros et al. 2019). The consequences of these feeding treatments
159 were considered on several life history traits further detailed below: morphometric features (body
160 condition, growth), energy resources (muscle lipid contents), somatic maintenance markers
161 (oxidative stress) and reproductive investment (gonadosomatic index).

162 In May 2017, around 1,000 sardines were captured at sea (see further details of fish biological
163 information at capture Table S1), and brought back to an experimental research facility, where
164 they were held in quarantine in outdoor tanks of 4.5 m^3 for 1 month and a half until confirmation
165 of the absence of pathogens (similarly to Queiros et al. 2019). During that time, sardines were
166 also weaned from live food (*Artemia nauplii*) to a mixture of aquaculture pellets of different
167 sizes: 0.1 mm, 0.3 mm and 0.8 mm at feeding rates between 1 and 2% of the biomass per day. At
168 the end of June sardines were moved into 2 indoor tanks of 3 m^3 each (Figure 1). Prior to

169 transfer, sardines were anaesthetized with benzocaine (140 ppm), their total length (± 0.1 mm)
170 and mass (± 0.01 g) measured so as to distribute them into homogeneous groups (i.e., similar
171 mean and standard error of size and mass between tanks) between the two tanks. Moreover, after
172 the two first months we switched the fish from one tank to the other, in order to buffer any
173 potential tank effect.

174 The experimentation started on June 27, 2017 and ended on March 5, 2018. The first phase (from
175 June 27 to November 16) was considered as the summer period with two possible scenarii that
176 aim to mimic contrasted natural conditions: (i) A “highly productive” year that was
177 experimentally mimicked by high food quantities (between 0.8% and 1.2% of the total fish
178 biomass, according to prevailing temperature) and large pellets size (1.2 mm) and (ii) a “low
179 productive” year characterized by smaller food quantities (between 0.4% and 1% of the total
180 biomass, according to prevailing temperature) and small pellets size (0.1 mm, see Figure 1).
181 These two contrasting pellet sizes are in the range of prey size in their diet (Le Bourg et al.
182 2015).

183 On October 25, each group of sardines was homogeneously divided into 4 sub-groups (following
184 the same procedure as in June), and transferred to 300 L tanks (8 tanks in total; Figure 1) in
185 preparation for the second phase of the experiment (from November 17, 2017 to March 5, 2018).
186 The second phase of the experiment (afterwards ‘winter’) started the first week when the
187 temperature dropped below 14°C i.e. mid-November (November 17th) which coincided with the
188 entry into reproduction during a natural breeding cycle for northwestern Mediterranean sardines
189 (Brosset et al. 2016a). Similarly, sardines reared in captivity over the last 4 years have initiated
190 spawning event only when the water temperature dropped below 14°C and have stopped
191 reproduction at the end of winter when temperature rose above 15°C. During this second phase,

192 half of the tanks remained in the same food condition as during summer, while the other half
193 switched. To sum-up, our experimental design ended with four treatments: (i) rich diet in
194 summer and winter (referred as Rich Summer/Rich Winter), (ii) rich diet in summer and poor
195 diet in winter (Rich Summer/Poor Winter), (iii) poor diet in summer and rich diet in winter (Poor
196 Summer/Rich Winter), and (iv) poor diet in summer and winter (Poor Summer/Poor Winter),
197 each composed of two tanks. On March 5, 2018 (when the reproductive period was over), the
198 experiment stopped and 120 sardines (30 per feeding treatment) were randomly sampled and
199 sacrificed by benzocaine overdose in order to study in-depth their physiological conditions. Sex
200 and maturity were determined by gonad observation at the end of experience. Mortality during
201 the experiment was very low, on average 4% (further details in Table S2 with mortality rate for
202 each tank).

203 Tanks were supplied with the same seawater (filtered and passing through UV light) at a renewal
204 of 10%/hours during both period ('summer' and 'winter'). All tanks were provided with
205 individual standardised light source mimicking the sunlight spectrum and mimicking natural
206 cycles including progressive dawns and sunrises. The photoperiod was thus weekly adjusted to
207 follow the natural cycle and seawater temperature was not controlled except to maintain a
208 minimum of 10°C and a maximum of 25°C. Finally, temperature and salinity recordings of tanks
209 were closely following the same trend over the entire period (Figure S1).

210

211 **2.2. Total length, body condition and growth (N = 972 individuals)**

212 Each sardine was tagged to allow individual monitoring of body growth. On August 29, 2017, a
213 tiny RFID tag (Biolog-id, Bernay, France, 0.03 g, or < 0.6% of the body mass of the leanest

214 sardine) was implanted in the dorsal muscle after being anaesthetized with benzocaine (140
215 ppm). Thereafter, total length (± 0.1 mm) and mass (± 0.01 g) were recorded individually every 4
216 weeks (later on named “biometry day”) until the end of the experiment. Sardines were fasting 24
217 hours before each biometry so weight would not be biased by stomach content. Relative body
218 condition of each sardine (N = 972) was calculated with the Le Cren index Kn as estimated by
219 Brosset et al. (2015):

$$220 \quad Kn = \frac{WW}{0.00607 \times TL^{3.057}} \quad (1)$$

221 where WW is the wet mass in g and TL is the total length in cm. This index compares the actual
222 mass of an individual with the theoretical mass expected for an individual of its size (based on
223 the size-weight relationship of tens of thousands of individuals fished *in situ*). Therefore, a value
224 of $Kn > 1$ means that the individual has a body condition higher than the average of the
225 population and *vice versa*.

226 Growth rates and condition rates were then estimated at different time scales. First, instantaneous
227 growth and condition rates were estimated as the change in length and condition from one
228 biometry day to the next one, divided by the number of days between them. Because of relative
229 measurement precisions (1mm) and the some extremely slow growth, it sometimes resulted in
230 negative growth rate $t-1 \rightarrow t$. To overcome this problem, we translated all instantaneous growth
231 rates by the minimum rate ever observed ($-0.28 \text{ mm.day}^{-1}$) considering that this should represent
232 a null growth. For each individual, a summer and a winter growth and condition rates were also
233 estimated as the slope of linear models of total length (mm) or body condition over time (day) (1
234 linear model per individual per period).

235 Before the start of individual monitoring (August 29), 130 and 108 individuals were measured in
 236 June and July, respectively, to adjust food quantity to total tank biomass. Since the individuals
 237 were not tagged yet, the data could not be linked to individual size or condition trajectories. The
 238 average condition and size measurements at these 2 dates are therefore presented only for
 239 information on the graphs and are not used in analyses. Further, between the 29th August and the
 240 26th September 2017 about 40% of individuals lost their tags. These individuals were retagged on
 241 September 26 and no tags were lost afterwards. In order to ensure that the lower sample size for
 242 this first month (due to tag lost) didn't affect our analysis we compared mean growth rates and
 243 condition rates (\pm SE) through time per treatment considering 3 subsamples (Figures S2 and S3):
 244 a) considering all data points available (N=603 in September and then 972 for all other month),
 245 b) the 603 individuals over the entire time series and c) only the 120 individuals sacrificed at the
 246 end of the experiment. Since results did not differ whatever the subsample considered, we
 247 present hereafter results based on all data available.

248 At the end of the experiment 120 individuals were sacrificed (30/treatment which were
 249 representative of their treatment (similar growth and condition rate), see Figure S2 and Figure
 250 S3). To obtain a growth rate for the entire experiment (referred as total growth rate), summer and
 251 winter growth were averaged weighted by the number of days of each period (equation (2)):

$$252 \quad total\ growth\ rate = \frac{growth\ rate_{summer} * days_{summer} + growth\ rate_{winter} * days_{winter}}{(days_{summer} + days_{winter})} \quad (2)$$

253 In order to obtain a trait independent of the reproductive investment, a second body condition
 254 index was calculated where gonads mass was removed from the individual's final weight
 255 (therefore only available at the end of the experiment for the N=120):

$$256 \quad Kn_{without\ gonad} = \frac{WW - GM}{0.00055 \times TL^{4.0498}} \quad (3)$$

257 where WW and GM are the final wet mass in g of individuals and gonads respectively and TL is
258 the final total length in cm. The two constants were estimated from our data based (> XXX
259 individuals) on the final size-weight without gonads relationship of the 120 individuals sacrificed
260 in March.

261 Total condition rate (i.e. over the entire experiment for the N=120) was then assessed
262 based on this second condition index. Equation (4) indicates how we assessed the gain/loss of
263 body condition for the entire experiment independently of the investment in reproduction:

$$264 \quad \text{Condition rate}_{\text{without gonad}} = \frac{Kn_{\text{without gonad}} - Kn_i}{(\text{days}_{\text{summer}} + \text{days}_{\text{winter}})} \quad (4)$$

265
266 where $Kn_{\text{without gonad}}$ is the individual final body condition as explained previously (equation (3))
267 and Kn_i is the initial body condition (equation (1)) at the start of the experiment. Because the
268 experiment started in summer, when individuals have not yet started to invest in reproduction,
269 we considered the mass of gonad to be null at that time (see Figure 2 in Brosset et al. 2016)

270 **2.3.Reproduction status at the end of winter (N=120 individuals)**

271 For each of the 120 sacrificed individual, sex and gonad mass were recorded. To estimate
272 sardines' reproductive investment, a gonadosomatic index (GSI, Alam and Pathak 2010) was
273 estimated as follows:

$$274 \quad GSI = \frac{\text{Gonad mass}}{\text{Individual mass}} \times 100 \quad (5)$$

275 Out of the 120 individuals, 6 individuals displayed non-active gonads (and 3 out of the 6 were
276 not sexually differentiated while all the other individuals presented mature gonads. Therefore we
277 had the sex for 117 sardines at the end of the experience.

278 **2.4. Physiological condition at the end of winter (N = 120 individuals)**

279 For each of the 120 individuals sacrificed at the end of the experiment, blood was collected from
280 the caudal vein with a heparinized 26G needle and transferred into 1.5 ml Eppendorf tubes.
281 Blood samples were centrifuged at 3000 g for 10 minutes at 4°C to separate plasma from cells,
282 which was collected and stored at -80°C until further oxidative status analyses. Portions of dorsal
283 epaxial muscle were also removed, immediately frozen in liquid nitrogen and stored at -80°C for
284 further lipid analyses.

285 **2.4.1. Individual oxidative status**

286 The physiological consequences of feeding treatment were studied by assessing the oxidative
287 stress status in plasma by measuring two biomarkers for antioxidant defenses (Total antioxidant
288 defenses, OXY and Superoxide dismutase enzyme activity, SOD) and two biomarkers for
289 oxidative damage (Reactive oxygen metabolite, d-ROMs and Thiobarbituric acid reactive
290 substances formed as a byproduct of lipid peroxidation, TBARs).

291 All sample measurements were performed in duplicate. Samples with a coefficient of variation
292 (CV) higher than 15% were re-run. Assays were performed on all individuals except for some
293 individuals for whom the amount of plasma was not sufficient to perform all tests, explaining the
294 differences in sample sizes among analyses. Sample sizes are reported in the text and figures.

- 295 ● d-ROMs and OXY :

296 According to Costantini and Dell’Omo (2006) reactive oxygen metabolites (d-ROMs) and total
297 antioxidant defenses (OXY) were estimated in plasma using the d-ROMs test and the OXY
298 Adsorbent test, respectively (Diacron International©, Grosseto, Italy). After incubation,
299 absorbance was measured at 555 nm with a microplate spectrophotometer. d-ROMs were
300 expressed in mg of equivalent $\text{H}_2\text{O}_2\cdot\text{L}^{-1}$ and the antioxidant defense capacity (OXY) in μmol
301 $\text{HClO}\cdot\text{mL}^{-1}$. The intra- and inter-plate CV were 4.5% and 3.1% for d-ROMs and 7.3% and 7.7%
302 for OXY, respectively.

303

304 • Superoxide dismutase (SOD) :

305 Superoxide dismutases (SOD) are important endogenous defense systems against free oxygen
306 radicals which catalyze the dismutation of superoxide radicals (O_2^- into hydrogen peroxide
307 (H_2O_2) and oxygen (O_2) ($2\text{O}_2^- + 2\text{H}^+ \rightarrow \text{O}_2 + \text{H}_2\text{O}_2$, Fridovich 1989). SOD is represented by
308 three isoforms, differing with metal ions in their active centers, Mn-SOD (SOD2) and Cu/Zn-
309 SOD (SOD1 and SOD3). In plasma, only SOD3 is present. Therefore, an increase in this enzyme
310 indicates good circulating neosynthesized antioxidant defense (Barry Halliwell & John M. C.
311 Gutteridge, 2007). Their concentration in plasma was estimated by colorimetry according to
312 Peskin & Winterbourn (2000). To normalize SOD concentration by protein content in plasma,
313 protein concentration in each sample was determined by the BCA method (Pierce, Thermo
314 Fisher Scientific, France). Four plasma samples lacked the required quantity to run duplicates.
315 Nonetheless, the intra- and inter-plate CV being respectively 8.4% and 3.4% for the SOD
316 estimation (always $<15\%$ for all duplicates), we considered the four samples that were run only
317 once reliable. After incubation at 37°C for 30 minutes, absorbance was measured at 450 nm with
318 a microplate spectrophotometer. For each plasma sample the SOD concentration was also

319 corrected by the protein content and expressed in units/ μg protein. The intra- and inter-plate CV
320 were 3.7% and 0.7% for the protein estimation.

321 • Lipid peroxidation (TBARS test) :

322 Finally, lipid peroxidation in the sardine plasma was estimated from the production of
323 malondialdehyde (MDA), which is one of the final products of lipid peroxidation (Draper &
324 Hadley 1990). The MDA content was determined by the “MDA colorimetric assay kit”
325 (Elabscience Biotechnology Inc.©). This assay measures the thiobarbituric acid (TBA) reactive
326 substances at 532 nm, following the methodology described by Draper & Hadley (1990). The
327 intra- and inter-plate CV for plasma samples were 2.3% and 1.5% respectively.

328 **2.4.2. Energy storage and reserve**

329 The energy storage capacities were examined by analyzing the lipid content of the dorsal muscle.
330 The lipids were extracted according to the method of Folch et al. (1957) and the content of each
331 class of lipids was measured in the muscle by chromatography, using an Iatroscan as detailed in
332 Sardenne et al. (2019). Phospholipids (PL), sterols (ST), acetone-mobile polar lipids (AMPL)
333 and alcohols (CLA) were grouped in structural lipids, while triacylglycerols (TAG),
334 diacylglycerols (DAG as TAG precursors) and free fatty acids (FFA) were grouped in reserve
335 lipids (Zhol et al. 1995, Tocher 2003, Lloret et al. 2013). The proportions of free fatty acids
336 (FFA) were also checked to ensure that the lipids had not been degraded during sample storage.
337 Here, the proportions ranged from 0% to 12%, significantly below the 25% limit recommended
338 by Parrish (1988).

339 2.5.Data analyses

340 2.5.1. Effects of feeding treatments on life history traits at the population level

341 At the end of both periods (summer and winter), the differences in size and body condition
342 between treatments were tested, using linear mixed model (LMM and pairwise post-hoc tests)
343 where tank was added nested in treatment as random factor to account for tank effect in winter.
344 Summer and winter growth rates and condition rates in response to treatments were also
345 investigated, similarly as above (LMM and pairwise post-hoc tests). To test the effect of the
346 individual's size at the beginning of summer and winter on summer and winter growth rate
347 respectively, we modeled the summer or winter growth rate (response variable) in relation to the
348 initial size (at the beginning of summer or winter), feeding treatment as well as their interaction
349 (explanatory variables). These analyses were run on N=972 individuals. We also ran our
350 different models on the subsample for which we have the sex (N = 117 individuals) in order to
351 test its effect. Sex was included in interaction with treatment and removed when non-significant.
352 Physiological conditions (plasma oxidative stress and muscle lipid content) and reproductive
353 investment differences between treatments for the N=120 individuals sacrificed at the end of the
354 experiment were examined, using parametric (LMM) or non-parametric (Kruskal-Wallis) tests
355 and associated post-hoc (Tukey or Dunn test), depending on residual normality. Sex was
356 included in interaction with treatment and removed when non-significant.

357 A multivariate Principal Component Analysis (PCA, Abdi and Williams 2010) approach was
358 also performed, using the N=120 individual sardines as objects and the summer growth and
359 condition rates (August to November), the winter growth and condition rates (November to
360 March), as well as the antioxidant defence biomarkers (SOD and OXY), the oxidative damage

361 biomarkers (TBARS and d-ROMs), the reserve in lipids and the gonadosomatic index at the end
362 of the experiment, as descriptors. The aim of this analysis was to summarize all the information
363 and investigate the relationships between descriptors and to examine the level of inter-individual
364 variability overall and within each feeding treatment.

365 **2.5.2. Investigating inter-individual variability and allocation trade-offs**

366 Van Noordwijk and De Jong (1986) demonstrated that correlations between competing traits (*e.g.*
367 growth, maintenance and reproduction) within a species may take any sign. If individuals differ
368 in their strategies, allocation trade-offs should occur and negative relationships between traits
369 would likely be observed (Stearns 1989). Yet, if heterogeneity in individual quality exists, “high-
370 quality” individuals should be able to display higher investment overall into all competing traits
371 than other individuals referred as “low-quality” individuals, resulting in positive relationships
372 among traits. We checked those possibilities first by analysing the inter-individual variance in
373 size and body condition over the different periods of sampling of our experiment with standard
374 deviation (SD) time series. However, those alternative hypotheses are not exclusive and trait
375 covariation could also depend on the environment (*e.g.* trade-offs appearing only under limiting
376 conditions, Hämäläinen et al. 2021). Therefore, we investigated how growth rate, condition rate
377 and GSI covaried and whether this depended on the feeding treatment, using various types of
378 regression models (see below). Each model was tested with and without the interaction of the
379 feeding treatment with the covariables (either growth rate, condition rate or GSI) and the best
380 models were selected, using the AIC criterion (Burnham & Anderson, 2004). When these
381 interactions were significant, we presented one model for each treatment to facilitate the analysis
382 of the results. The normality of the residuals of each model was analysed visually with a
383 quantile-quantile plot (Q-Q plot, Ghasemi and Zahediasl 2012) or through a Shapiro-Wilk’s test,

384 depending on the number of observations. When data were not independent from each other due
385 to repetitions within individuals (e.g. body condition and body size over time), a mixed model
386 was used with the individual effect sets as a random intercept, either through a linear mixed
387 model (LMM, Zuur et al. 2009) or a generalized linear mixed model (GLMM, Zuur et al. 2009),
388 depending on the distribution of the data.

389 *2.5.2.1 Modelling growth and energy storage*

390 We first tested how sardines allocated energy between growth and body condition at each time
391 step during winter only depending on body condition at the start of this time step, using the
392 initial N=972 individuals. As the interaction with treatment was significant (see section results
393 below), we conducted for each feeding treatment a GLMM (with a gamma link function and with
394 the individual effect set as a random intercept) where individuals growth rates from $t-1$ to t
395 during winter were dependent on their changes in body conditions over that same period and
396 their body conditions at the beginning of $t-1$ as well as their interactions (equation (6) (N = 972)).
397 In order to test for sex effect we also ran sub-models on the 120 individuals for which sex was
398 available. Since sex had no effect it was removed from the final model.

$$399 \quad \text{Growth rate}_{t-1 \rightarrow t} = \text{Condition rate}_{t-1 \rightarrow t} \times \text{Condition}_{t-1} + (1 | ID) \quad (6)$$

400 Where “ID” is used here for individual (Individual tag number considered as categorical for
401 repeated measurement).

402 *2.5.2.2 Modeling growth, energy storage and reproduction*

403 As body condition index includes energy stored for reproduction, we examined more precisely
404 the links between reproduction, growth and maintenance, using the 120 individuals sacrificed at
405 the end of the experiment. Therefore, we assessed whether reproductive investment (GSI) was

406 constrained by energy investment in growth (total growth rate, equation (3)) and in body
407 condition (condition rate_{without gonad}, equation (4)) over the entire experiment, using a generalized
408 linear model (GLM), with a gamma link function, for each feeding treatment. In order to test for
409 sex effect we added sex in interaction. When sex had no effect it was removed from the final
410 model.

411 *2.5.2.3 Summarizing the different energy allocation strategies*

412 Using the 120 individuals sacrificed at the end of the winter period, we investigated the different
413 energy allocation strategies through a hierarchical clustering analysis (Johnson 1967). This
414 analysis was performed on total growth rate, total condition rate_{without gonad} and GSI, using
415 Euclidean distances on normalized data (data were first centered by treatment to remove the
416 direct effect of the feeding treatment on the absolute values of GSI, growth rate and condition
417 rate) and the Ward's agglomerative clustering method (Ward 1963). To test for physiological
418 costs associated with the identified strategies (i.e. the different clusters), differences in oxidative
419 damage and antioxidant defense between clusters were investigated using one-way analyses of
420 variance (LM and pairwise post-hoc tests). In order to account for known sex effect on GSI we
421 realized separate analyses for males and females. The best clustering scheme was identified
422 using the function *NbClust* (Charrad et al. 2014) which tests 30 methods that vary the
423 combinations of number of clusters and distance measures for the hierarchical clustering. To
424 evaluate the effect of the individual's size at the beginning of the experiment on their potential
425 strategies, composition of initial size in each cluster for both sexes were assessed.

426 Analyses were performed with the statistical open source R software v.4.1.1 (R Core Team
427 2020) using the FactoMineR (Lê et al. 2008), the nlme (Pinheiro et al. 2021), the lsmeans (Lenth

428 2016), and the factoextra (Kassambara & Mundt 2020) packages. Values are indicated as mean \pm
429 standard error (SE) and all statistical tests were performed at a significance level of 0.05.

430 **3. Results**

431 **3.1. Effects of feeding treatments on life history traits at the population** 432 **level**

433 **3.1.1. Compensatory growth**

434 At the end of summer (vertical dotted line in Figure 2a and 2b), rich summer feeding conditions
435 led to individuals of larger size (LM; $F = 225.48$; $P < 0.001$; Table S3) and in better condition
436 (LM; $F = 689.58$; $P < 0.001$; Table S3). Well-fed sardines grew twice as fast as those facing poor
437 summer feeding conditions (0.14 ± 0.004 mm/day and 0.07 ± 0.004 mm.day⁻¹ respectively) (LM;
438 $F = 119.29$, $P < 0.001$) and body condition rates increased 5 times more for sardines in rich vs.
439 poor feeding conditions (LM; $F = 439.72$; $P < 0.001$, Figure 2c and 2d, Table S3). In summer,
440 smaller sardines in rich feeding condition grew significantly less than larger ones whereas
441 smaller sardines in poor feeding condition grew significantly more than larger ones, indicating
442 that initial size is important but its effect on growth rate is treatment-dependent (LM; $P < 0.01$,
443 Table S4, Figure S4). In none of our model considering size and growth rate the sex had any
444 effect. However, males poorly fed displayed better body condition (1.02 ± 0.02 and 0.95 ± 0.05
445 for male and female respectively, Figure S5) and higher body condition rates than females in the
446 same feeding condition which presented body condition rates over summer no significantly
447 different from zero (Student's t -test; $t = -0.090386$; $P = 0.93$). At the end of the winter, the four
448 treatments led to four significantly distinct groups in terms of total length and body condition
449 (i.e. Rich Summer/Rich Winter > Rich Summer/Poor Winter > Poor Summer/Rich Winter >

450 Poor Summer/Poor Winter for both variables, Post-hoc HSD-Tukey; $P < 0.001$; Figure 2a and
451 2b). Individuals well fed throughout the entire experiment grew 1.5 to 2 times faster during
452 winter than individuals in the intermediate Rich Summer/Poor Winter and Poor Summer/Rich
453 Winter treatments (Post-hoc HSD-Tukey; $P < 0.001$) and 6 times faster than individuals poorly
454 fed all along (Post-hoc HSD-Tukey; $P < 0.001$). For the latter, growth almost stopped, but was
455 still significantly different from zero over winter (Student's t -test; $t = 9.2838$; $P < 0.001$).
456 Interestingly, sardines from the Poor Summer/Rich Winter treatment strongly increased their
457 body condition over the winter ($10.7 \cdot 10^{-4} \text{ day}^{-1}$), between 1.5 and 7 times more than extreme
458 treatments ($7.4 \cdot 10^{-4} \text{ day}^{-1}$ and $1.5 \cdot 10^{-4} \text{ day}^{-1}$ for the Rich Summer/Rich Winter and Poor
459 Summer/Poor Winter treatments respectively, Post-hoc HSD-Tukey; both $P < 0.001$), while
460 sardines experiencing the opposite changes (from rich to poor) decreased in condition ($-4.2 \cdot 10^{-4}$
461 day^{-1} , Post-hoc HSD-Tukey; $P < 0.001$). Tank (for a given feeding treatment) had no effect on
462 body condition and length over time and was therefore removed from the analyses. According to
463 the AIC, the better model for the winter growth rate included both the initial size, the treatment
464 and their interactions. Nonetheless, only the feeding treatment effect was significant while the
465 initial size remained non-significant globally and in interactions (Table S5). Sex had no effect in
466 all models including size and growth rate. Males poorly fed all along displayed better body
467 condition than females for the same feeding treatment ($P < 0.01$, Figure S5) while no significant
468 differences between sexes were found for the other treatment. Similarly male and female in the
469 same feeding condition revealed similar body condition rates over winter.

470 **3.1.2. Plasticity in reproduction**

471 Gonadosomatic indices (GSI measured at the end of the experiment) for the Rich Summer/Rich
472 Winter treatment (median: 7.9%) were about twice as high as those for the intermediate

473 treatments (medians: 3.8% and 2.6% for the Rich Summer/Poor Winter and Poor Summer/Rich
474 Winter treatments, respectively) and 12 times higher than for sardines always fed in poor
475 conditions (median: 0.7%, Figure 3). A significant sex effect on the reproductive investment was
476 found ($P < 0.001$), males displaying 2 to 3 times higher GSI than females, which held true in
477 each treatment (Figure S6).

478 **3.1.3. Costs in terms of maintenance**

479 No significant differences between sex and tanks (for the same feeding treatment) for plasma
480 oxidative state and muscle lipid contents were found.

481 ● Individual oxidative status

482 Overall, sardines from the Rich Summer/Rich Winter treatment presented the lowest level of
483 antioxidant defenses in both OXY and SOD (Figure 4a, 4b) although these differences were not
484 always significant with respect to sardines from other treatments. Sardines from the Poor
485 Summer/Poor Winter treatment presented low to average OXY levels, but displayed endogenous
486 antioxidant SOD levels twice as high as those under the intermediate treatments (Post-hoc HSD-
487 Tukey; $P < 0.01$; Figure 4b) and five times as high as those under the Rich Summer/Rich Winter
488 treatment (Post-hoc HSD-Tukey; $P < 0.001$). Furthermore, sardines from the Rich Summer/Rich
489 Winter treatment displayed lower oxidative damages than sardines of other treatments (d-ROMs
490 and TBARS, Figure 4c, 4d). No difference in oxidative damages was observed among the other
491 three treatments.

492 ● Lipid content

493 Reserve lipid concentration in muscle gradually increased with the improvement of the feeding
494 conditions. Reserve lipids for Rich Summer/Rich Winter treatment were 2 to 7 times higher than

495 those of the three other treatments. Sardines from the Poor Summer/Poor Winter treatment
496 presented the lowest concentration of reserve lipids (Post-hoc Dunn's test, $P < 0.001$). On the
497 other hand, structural lipids were similar among all four treatments (Kruskal-Wallis; $H = 2.95$; P
498 > 0.05 ; Figure S7).

499 **3.1.4. Multivariate analysis**

500 The first 2 components of the PCA explained 50.2% of the total variance observed. The main
501 contributing variables to the first axis were winter growth and reserve lipids, whereas d-ROMs
502 and OXY were the two main contributors to the second axis (Figure S8). The PCA tends to
503 disentangle extreme treatments. Individuals from Rich Summer/Rich Winter treatment were
504 mostly characterized by high winter and summer growth, high summer body condition, high GSI
505 (i.e. reproduction investment), high lipid body and low oxidative states (OXY, d-ROMs, TBARS
506 and SOD) while individuals from Poor Summer/Poor Winter treatment generally displayed the
507 opposite (Figure 5). Individuals from intermediate treatments, were in-between, close to the
508 barycenter, although individuals from the Poor Summer/Rich Winter and Rich Summer/Poor
509 Winter treatments were closer to those of the Poor Summer/Poor Winter and Rich Summer/Rich
510 Winter treatments, respectively (Figure 5).

511 **3.2. Diversity of individual life-history strategies**

512 SD in total length from the Rich Summer/Rich Winter and Rich Summer/Poor Winter
513 individuals were higher than those of the two other treatments and increased continuously over
514 the experiment (Kruskal-Wallis; $\chi^2 = 15.923$; $P < 0.001$; Figure S9a).

515 The SD in body condition of the Rich Summer/Rich Winter and Rich Summer/Poor Winter
516 treatments decreased throughout the experiment, while SD of the Poor Summer/Rich Winter

517 treatment seemed to stabilize from September and those of the Poor Summer / Poor Winter
518 increased after September. At the end of winter, the sardines from the rich treatment (Rich
519 Summer/Rich Winter) showed less variance than fish reared in poor feeding condition
520 throughout the experience, while intermediate treatments are in-between but still significantly
521 different from one another with Rich Summer/Poor Winter lower than Poor Summer/Rich
522 Winter (Figure S9b).

523 **3.2.1. Trade-off or individual quality between growth and investment in body** 524 **condition**

525 Because sardines were monitored repeatedly over time, we investigated the allocation trade-off
526 towards growth vs. body condition every month during winter only according to the initial
527 condition and the treatment (see eq.6). As the interaction with the treatment was always
528 significant, we conducted a GLMM for each feeding treatment. In all models, the random effect
529 for individuals contributed to an increase of 7% to 18% of the R^2 . For all feeding treatments
530 during winter, sardines having good body condition at time $t-1$ invested more in body size
531 growth (positive relationship) except for sardines from the Rich Summer/Rich Winter treatment
532 where no significant effect was detected between these two traits (Tables S5). Results clearly
533 highlighted that whichever the diet, sardines investing in their body condition invested less in
534 their body size growth leading to negative relationships between these two traits (Figure 6, Table
535 S6 to Table S7). Yet, this decrease varied in intensity depending on body condition at $t-1$ for
536 sardines of the Poor Summer/Rich Winter feeding treatment (Figure 6b, significant interaction,
537 Table S7). It then appeared that the larger the body condition ($t-1$), the steeper the decrease in the
538 growth rate (t) with the condition rate (t) (Figure 6b).

3.2.2. Trade-off or individual quality between growth, investment in body

condition without gonad and reproduction

We then focused on the 120 individuals sacrificed at the end of the experiment to study possible trade-offs between investment in growth, body condition independently of the reproductive investment (condition rate_{without gonad}) and reproduction. As in the previous analysis, the treatment interaction was significant, so that a model was conducted for each feeding treatment. Generalized linear model suggested that neither energy investment in growth nor in body condition, constrained the reproductive investment in any of our experimental groups (Table S10 to S13). On the contrary, sardines from the Poor Summer/Poor Winter treatment displayed a positive relationship between growth and reproductive investment, suggesting that sardines who grew the most also developed the highest GSI (Tables S11). However this last result must be tempered considering the medium R^2 ($R^2 = 0.41$).

3.2.3. Energy allocation strategies

To investigate potential differences in energy allocation strategies among the 120 individuals sacrificed at the end of the winter, a clustering analysis on growth, condition rate_{without gonad} and GSI was performed separately for both sex (in order to account the known effect of sex on GSI). Note that clustering analyses were performed on the 117 individuals for which we had information on sex. The best clustering scheme was with 2 clusters for males (Figure 7a) and 3 clusters for females (Figure 7b). The composition in feeding treatment as well as the size at the beginning of the experiment and the maturity of individuals (at the end of the experience) of each cluster was also assessed.

All four feeding treatments were represented in each cluster for both sex except in the third cluster for females where the Rich Summer/Rich Winter treatment was absent (Figure S10 and

562 S11). No clear maturity-related pattern was identified as only 6 sardines of the 120 sacrificed at
563 the end of the experiment were immature. The distributions of initial lengths (measured in
564 August 2017, at the beginning of the experiment) did not display any significant difference
565 between clusters for both sex (Figure S16). For males, the first cluster (56% of individuals)
566 included sardines with an important investment in condition rate (1.4 times higher than in the
567 other cluster; LM, $P < 0.001$, Figure S12) at the detriment of growth rate and GSI. Individuals of
568 the second cluster (44%) are characterized by lowered condition rates, but invested more in the two
569 other traits, especially in GSI, *i.e.* displaying GSI between 2 times higher ($7.7 \pm 0.4 \%$) than the
570 first cluster ($3.6 \pm 0.4\%$, LM, $P < 0.001$, Figure S12). For females, groups 2 and 3 look quite
571 similar to those identified for males, *i.e.*, a group (39% of the individuals) presenting an
572 important investment in body condition (1.4 times higher than the other cluster; LM, $P < 0.001$,
573 Figure S13) with moderate growth rate and GSI and a group (15% of fish) with low condition
574 rates but higher growth rate and especially GSI (being between 2 to 4 times higher than for the
575 first two clusters, Post-hoc HSD-Tukey, $P < 0.001$, Figure S13). The first cluster (46% of
576 individuals) included sardines favouring investment in growth rate with low GSI and body
577 condition rate, but differences were not significant with the other cluster $P > 0.05$, Figure S13).
578 Sardines appeared to favour one trait over another, in particular for females or even two traits for
579 the second and third cluster for males and females respectively.

580 Finally, no significant differences in antioxidant defence and oxidative damage between clusters
581 for male and female were found except for male where cluster 1 displayed 1.6 times higher
582 endogenous antioxidant SOD level than the second cluster (Kruskal test, $P < 0.05$, Figure S14
583 and S15).

584

585 4. Discussion

586 Life history trajectories reflect how animals manage the investment of available energy in
587 competing traits like growth, reproduction and lifespan (McEwen & Wingfield 2003). While
588 such trade-offs are the heart fitness optimization strategies in a given environment,
589 understanding their intimate mechanistic links and plasticity may enable us to assess more
590 precisely the present effects of global change. Our experimental study focuses on the energy
591 allocation trade-offs in the north-western Mediterranean sardines, to shed light on possible
592 mechanisms involved in the unusual decline in fish size and condition (Van Beveren et al.
593 2014a). Such changes are currently thought to derive from a bottom-up control, i.e., modification
594 of either size and/or quantity of sardine preys (Brosset et al. 2016a, Saraux et al. 2019).
595 Therefore, we investigated how resource temporal variability (in quantity and size) impacted
596 their main life-history traits through a long-lasting experiment on 972 adult sardines. We focused
597 on four questions:

- 598 (i) When feeding conditions improve, do sardines exhibit compensatory growth?
599 (Mangel & Munch 2005);
- 600 (ii) How plastic are sardines in terms of reproductive investment? Are sardines strictly
601 “capital-breeders” as usually considered (Ganias 2009)?
- 602 (iii) What are the costs in terms of maintenance of different energy allocation strategies
603 (Metcalf & Monaghan 2001, Mangel & Munch 2005)?
- 604 (iv) How can we explain inter-individual variability in these traits (reproduction, growth
605 and somatic maintenance)? Do they display different energy allocation strategies

606 (Reid et al. 2010) or does it rely exclusively on individual quality and heredity
607 (Marchand & Boisclair 1998, Wilson & Nussey 2010, Bergeron et al. 2011b)?

608 **4.1. Compensatory growth**

609 Although compensatory growth has been advocated for some fish (Ali et al. 2003), the present
610 study did not confirm such a process for the Mediterranean sardines, as individuals from the Poor
611 Summer/Rich Winter feeding treatment displayed slower growth rates than sardines fed in rich
612 conditions all along the experiment. Similarly to our results, gilthead seabream (*Sparus aurata*)
613 that were starved for 1 or 2 weeks showed no sign of compensatory growth during the following
614 8-weeks re-feeding period (Peres et al. 2011). Rather, when sardines went from poor to rich
615 conditions, they seem to use this new income of energy to rebuild their reserves by increasing
616 their body condition (Poor Summer/Rich Winter has the highest condition rate in winter).
617 Further, Rich Summer/Poor Winter sardines were the only ones to exhibit a decrease in body
618 condition during winter, confirming energy limitation during winter. However, their growth rates
619 remained higher than those of sardines fed poorly all along the experiment. Surprisingly, growth
620 rates of fish from Rich Summer/Poor Winter treatment appeared higher than those of fish from
621 Poor Summer/Rich Winter, suggesting the importance of a pre-acquired energy capital to derive
622 energy for growth. This is also supported by the fact that growth rates observed over a month
623 were positively correlated with the body condition at the beginning of that month. Still, when
624 comparing sardines with a same capital (i.e. Rich/Rich with Rich/Poor and Poor/Rich with
625 Poor/Poor), growth was still higher for sardines from rich feeding conditions than sardines fed in
626 poor conditions during winter, highlighting the additional importance of income energy
627 resources on growth. Altogether, our results indicate that an increase in energy resources might
628 be immediately allocated toward body condition, a fast-adjusted variable, while the effects of

629 feeding conditions on growth might be delayed over time as suggested by Peck et al. (2015) who
630 highlighted preferential allocation of food energy to restore body mass in recently re-fed fish.
631 This pattern further agrees with results found in the Gulf of Lions for anchovy and sardine,
632 where both species showed a decrease in body condition before a decrease in growth (Van
633 Beveren et al. 2014).

634 **4.2. Plasticity in reproduction**

635 Some processes, such as reproductive investment, seem to only take place after reaching a
636 critical mass/size/body condition (Asher & Cox 2013). In the Mediterranean Sea, sardines are
637 believed to reproduce in winter based on the energy capital they have built in the previous
638 summer (Ganias 2009). In this study, we indeed confirmed the importance of such a capital,
639 individuals from the rich treatment in summer displaying high GSI. However, such a statement
640 need to be put into perspective since individuals from the same rich treatment in summer differed
641 according to their winter feeding conditions (GSI in Rich/Rich being higher than GSI in
642 Rich/Poor). Similarly, individuals from intermediate treatments (Rich/Poor and Poor/Rich)
643 displayed similar reproductive investment (GSI), which is not in line with the vision of a strict
644 “capital-breeder” usually attributed to the Mediterranean Sardine (Aldebert & Tournier 1971).
645 Thus it appears that sardines reproductive behaviour could be more opportunistic than usually
646 assessed without a defined underlying strategy. This was previously suggested by Nunes et al.
647 (2011) for Atlantic sardine from the Portuguese coast and by Ganias (2009) for Atlantic sardine
648 from the Eastern Mediterranean Sea. Similarly, Hunter & Leong (1981) showed for the northern
649 anchovy, *Engraulis mordax*, another multiple spawning clupeid with indeterminate fecundity
650 that almost 2/3 of reproductive expenditure might be financed from fat reserves accumulated
651 during the preceding feeding season whilst the remaining 1/3 comes from direct feeding. We

652 suggest that this plasticity in the energy allocation in reproduction could help sardines to cope
653 with the recent warming trends. Indeed according to Sommer and Lengfellner (2008) climate
654 change seems to lead to weaker phytoplankton spring bloom and favor planktonic chains of
655 smaller size which would result in poorer feeding condition for sardines at the end of their
656 reproductive period. Moreover, the GSI was systematically higher for males than for females for
657 all feeding treatments at the end of their reproductive period. This difference between sexes has
658 also been reported for Atlantic sardine along the Moroccan coast (Amenzoui et al. 2006). The
659 reserve lipids showed similar pattern for males and females of the same feeding treatment,
660 suggesting the way in which energy was stored was the same for both sexes. Similarly, Caponio
661 et al. (2006) found no significant difference in lipid content between male and female Atlantic
662 sardine in the Ionian Sea.

663 **4.3. Cost in term of maintenance**

664 We assessed the potential costs of maintenance, as a result of environmental constraints in
665 resource availability, using oxidative balance as integrative markers of metabolic costs. Plasma
666 oxidative state was relatively unaffected by the different feeding treatments. Individuals from the
667 treatment with rich feeding conditions in summer and winter presented the lowest oxidative
668 damage and antioxidant defences. This suggests that when feeding conditions were abundant,
669 sardines could preserve a balanced oxidative stress despite displaying high growth rates. On the
670 contrary, individuals facing poor feeding conditions during summer and/or winter displayed
671 higher levels of oxidative damages (d-ROMs and TBARS), suggesting that dietary restriction
672 during growth and/or reproduction ultimately led to physiological costs (Monaghan et al. 2009).
673 These results are in line with a recent study showing that sardines in poor condition optimize
674 mitochondrial coupling efficiency (consume less oxygen than sardine in rich feeding condition to

675 produce a given amount of ATP) which may result in an increase of ROS production (Thoral et
676 al. 2021). In addition, individuals poorly fed in both summer and winter had high concentrations
677 of antioxidant enzyme SOD at the end of the experiment, which suggests an attempt to
678 compensate for possible deficiencies in exogenous antioxidants by increasing the endogenous
679 (neo-synthesized) antioxidant capacity. These results are consistent with previous work on
680 gilthead seabream, which found significant increases in MDA levels (lipid peroxidation control)
681 and SOD activity (as well as other antioxidant enzymes) as a consequence of food restriction
682 (partial or total, Pascual et al. 2003).

683 Previous studies suggest that oxidative stress may cause physiological trade-offs with
684 reproduction, so that greater investment in reproduction may reduce the resources available for
685 basic maintenance costs (Ilmonen et al. 2000, Alonso-Alvarez et al. 2004). However, our results
686 indicated that individuals seemed to be able to remain at a physiological optimum regardless of
687 resource availability. Thus, the oxidative balance did not necessarily appear as a marker of cost,
688 but rather as a life-history constraint as suggested by Metcalfe and Alonso-Alvarez (2010) and
689 Stier et al. (2012). However, studies focusing on the associations between body size, energy
690 metabolism, oxidative stress and lifespan suggested that results of intra- and interspecific
691 comparisons are difficult to generalise, and highlight the complex links between these life history
692 traits (Speakman 2005).

693 **4.4. Individual quality**

694 The PCA approach further highlighted a high degree of individual variability within each
695 treatment, in terms of metabolic costs (oxidative damage and antioxidant defences) and life
696 history traits (growth, condition and reproduction investment). Yet, this variability manifested
697 itself differently depending on the feeding treatment. SD of individual size from sardines of the

698 Rich Summer/Rich Winter treatment increased while the SD of their body condition decreased. It
699 appears that they tended towards a common (rather high and not limiting) body condition, but
700 that their structural growth varied greatly from one individual to another due to other factors,
701 such as individual quality (Wilson & Nussey 2010). Conversely, the SD in body condition of
702 individuals poorly fed in summer and winter tended to increase over time (and was higher than
703 the other 3 treatments), indicating that some individuals managed to accumulate more energy
704 reserves over the experiment than others. Nonetheless, the SD in size remained low for this
705 treatment, due to low to null growth. This suggests that when facing poor conditions, individuals
706 could hardly invest in structural growth, whatever their body conditions. Altogether, these results
707 tend to advocate for different individual qualities in the Mediterranean sardine population.
708 Theoretically, individual quality differences in a given environment can be explained by
709 variations in their capacity to acquire, efficiency in processing and using resources (Van
710 Noordwijk & De Jong 1986). Early-life experiences (which we did not control in this study) may
711 also explain differences between individuals. Indeed, it has been suggested that the early
712 environment can help shape a phenotype adapted to the conditions the organism is most likely to
713 experience in its adult environment (Costantini et al. 2012). Variability in fish growth is often
714 interpreted as a result of density-dependent process due to intra-specific competition for a limited
715 resource among individuals of similar age-classes (e.g. Lorenzen and Enberg 2002). Indeed, it is
716 often thought that larger individuals have an advantage over smaller individuals in competition
717 due to their higher swimming capacity and consumption capacity (Lundberg & Persson 1993).
718 This in return should also decrease their probability of being predated, hence the importance of
719 growing fast. Still, numerous other explanations can be proposed to explain differences in energy
720 acquisition: (i) the potential inter-individual competition is not only size-dependent, but also

721 linked with individual behavioural differences (“bolder” individuals may have better access to
722 food than “shy” ones, Réale et al. 2007) and (ii) for indeterminate growing animals, body
723 condition is of greater interest for individual fitness (*i.e.* enhancing the chances of individual
724 survival and/or future reproduction, Bêty et al. 2003). To distinguish between such hypotheses
725 would require further work, possibly through behavioural observations of individuals feeding.

726 Apart from quality, inter-individual differences can also be interpreted as different energy
727 allocation strategies. In particular, one of the hypotheses to characterise these differences
728 between individuals lies in the differences in the energy pool devoted to reproduction. Our GLM
729 outputs suggest that sardines invested in reproduction regardless of their investment in body
730 condition and growth. These results are in accordance with Brosset et al. (2016b) who
731 highlighted that fish can maintain high reproductive investment potentially at the cost of other
732 traits which might explain the present disappearance of old and large individuals in the Gulf of
733 Lions. This preferential allocation of energy to gonad maturation was also observed in Atlantic
734 herring in the Baltic Sea (Rajasilta et al., 2015). Furthermore, we observed between two and
735 three main energy allocation strategies at the individual level in this study depending on sex: (i)
736 favouring body condition displayed for both sexes (56% of males and 39% of females), (ii)
737 favouring growth only for female (46% of females) or (iii) investing in both reproduction and
738 growth for both sexes (44% of males and 15% of females). Our results from the cluster analysis
739 highlighted a trade-off between growth and reserve storage, which was also displayed by the
740 GLMM outputs (negative correlation between growth rate (t) and condition rate (t)). However,
741 some individuals (*i.e.* those of the second cluster for males and the third cluster for females) were
742 capable of investing in both growth and reproduction whatever the treatment indicating that
743 despite different food limitations, some individuals can maintain simultaneously growth and

744 reproduction independently of their initial size. In this study, temperature seemed to be the main
745 driver of this trade-off. At colder temperatures, sardines may invest in condition and
746 reproduction but not in growth, even if feeding availability increases. Moreover, costs in terms of
747 maintenance and oxidative balance were relatively unaffected between the different strategies.
748 This clearly tends to invalid the hypothesis of a compromise between these two traits at the
749 individual level, as this has already been stressed at the population level on a number of taxa (see
750 Cam et al. 2002, Hamel et al. 2009).

751 **5. Conclusion**

752 Our results highlighted the impact of the seasonal variations in food availability on growth,
753 individual energy reserves and reproduction. Food resources during the summer period had a
754 major effect on energy reserves and growth, thus limiting the maximum size and body condition
755 achieved at the end of winter. The negative effects of a summer food restriction were still visible
756 during winter. These effects, also known as carry-over effects, have been documented in many
757 species and play a major role in energy allocation trade-offs between growth, maintenance and
758 reproduction (Mangel and Munch 2005, Norris & Marra 2007). In addition, food restrictions
759 during growth and/or reproduction period resulted in physiological costs through increased
760 oxidative damage, which sardines attempt to compensate by an overexpression of endogenous
761 antioxidant defenses (SOD). As increasing temperature favors weaker planktonic bloom and
762 phytoplankton of smaller size climate change might actually accelerate and amplify such
763 phenomenon. Mediterranean sardines did not show any compensatory growth, did not appear to
764 be “capital breeders” *sensu stricto* and tended to display different individual qualities in their

765 physiological adaptations. As sardines can live over 7 years in the wild, assessing the long-term
766 costs on individual longevity and subsequent reproductive output remain to be established.

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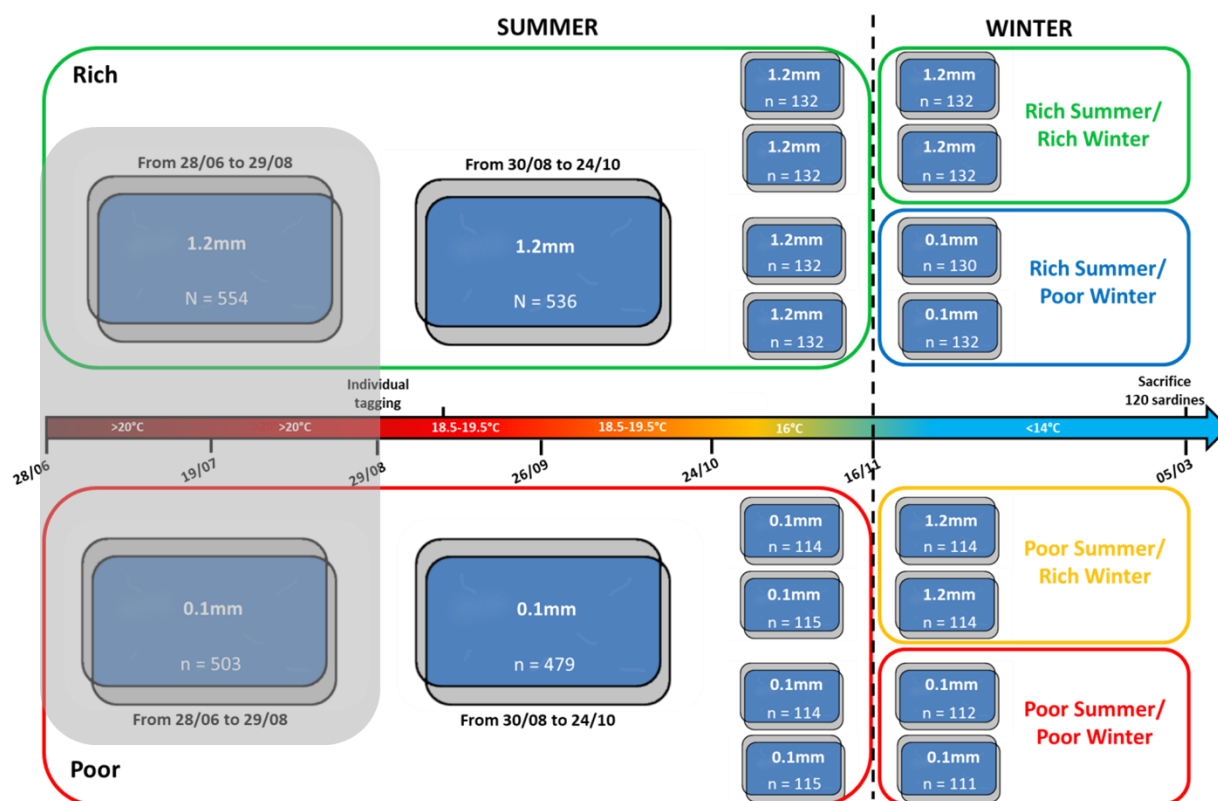
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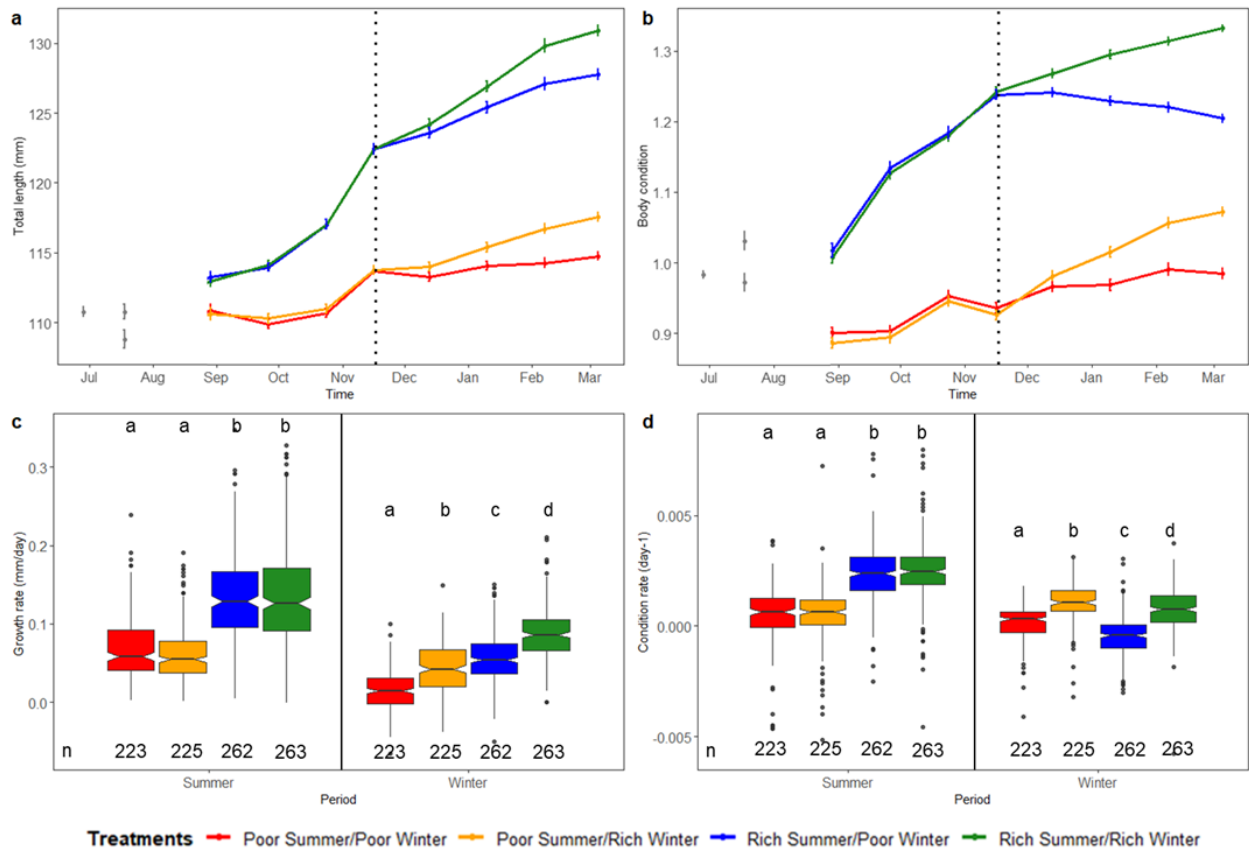
995 **Figures**



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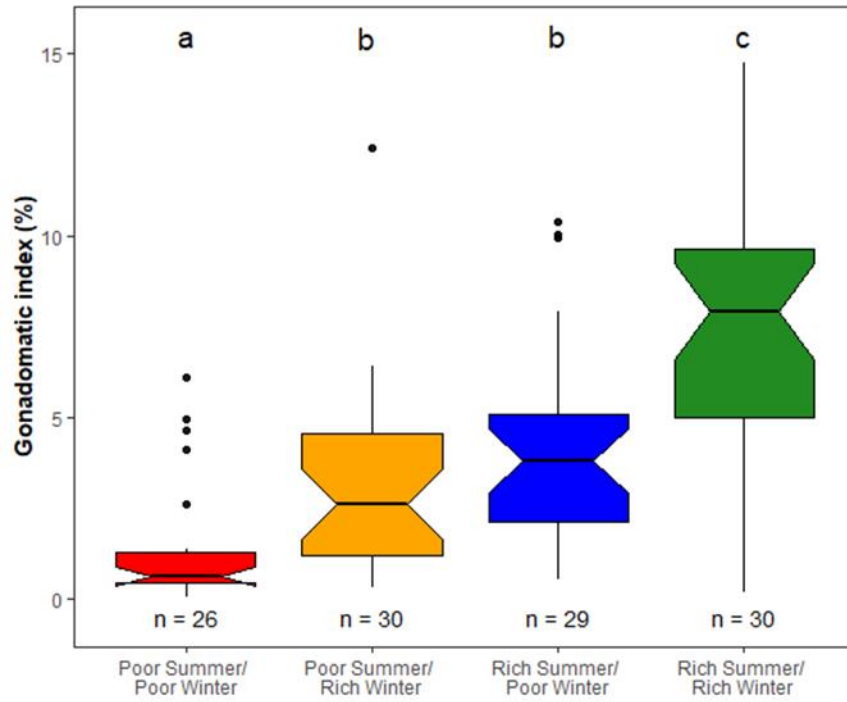
997 **Figure 1:** Design of the 8-month experiment. The experiment is divided into two periods
 998 separated by the dotted vertical line: summer for 4 and a half months with average to warm
 999 temperatures (from 16°C to over 20°C) and winter for 3 and a half months, corresponding to the
 1000 breeding season of sardines (between 13°C and 14°C). First 2 tanks of 3 m³, followed by 8 tanks
 1001 of 0.3 m³ were used. Pellet sizes (0.1 mm and 1.2 mm) and the quantity of food as a percentage
 1002 of fish biomass (0.4% to 1.2%) are indicated for each tank. Individual tagging is indicated by the
 1003 blue arrow on August 29, 2017, before which individual size and body condition could not be

1004 monitored (greyed area). Temperature ranges are indicated for each time step. The end of the
 1005 experiment and the sacrifice of the 120 individuals randomly sampled for the study of
 1006 physiological conditions are indicated by the red arrow on March 5, 2018.
 1007



1008
 1009 **Figure 2:** Time series of mean (\pm SE) total length (a) and body condition (b) per feeding
 1010 treatment and boxplots of summer and winter growth rates (c) and condition rates (d) for the four
 1011 treatments. Values in June and July based on a subsample are indicated in grey as individual
 1012 monitoring started from August 29th, 2017. Sample size for each treatment is given below the
 1013 boxes. Boxplot with different superscript letters are significantly different ($P < 0.05$). The
 1014 outliers are represented by black dots.

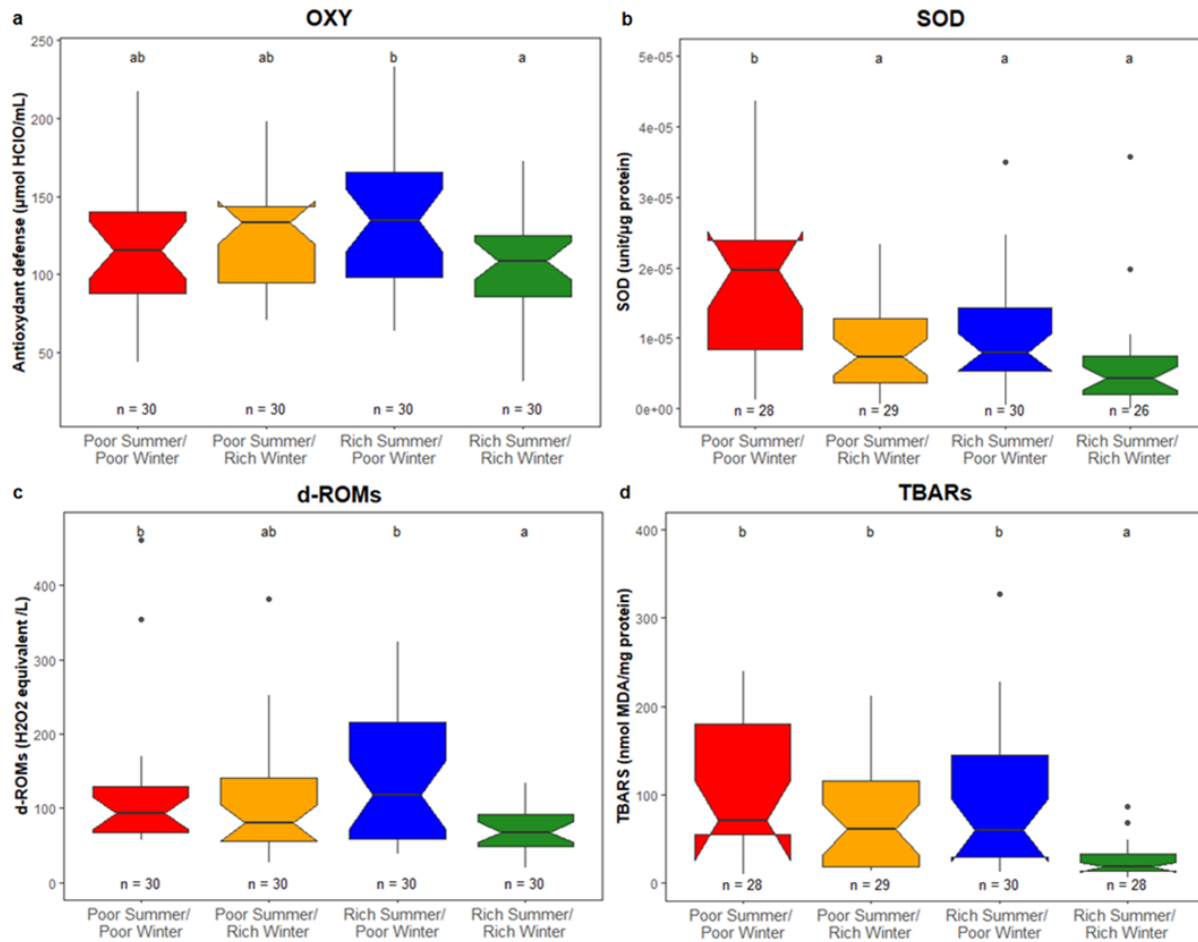
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1017 **Figure 3:** Gonadosomatic indices at the end of the experiment for each treatment. The sample
1018 size is indicated under each boxplot. Outliers are represented by black dots. Boxplots with
1019 different letters are significantly different ($P < 0.05$).

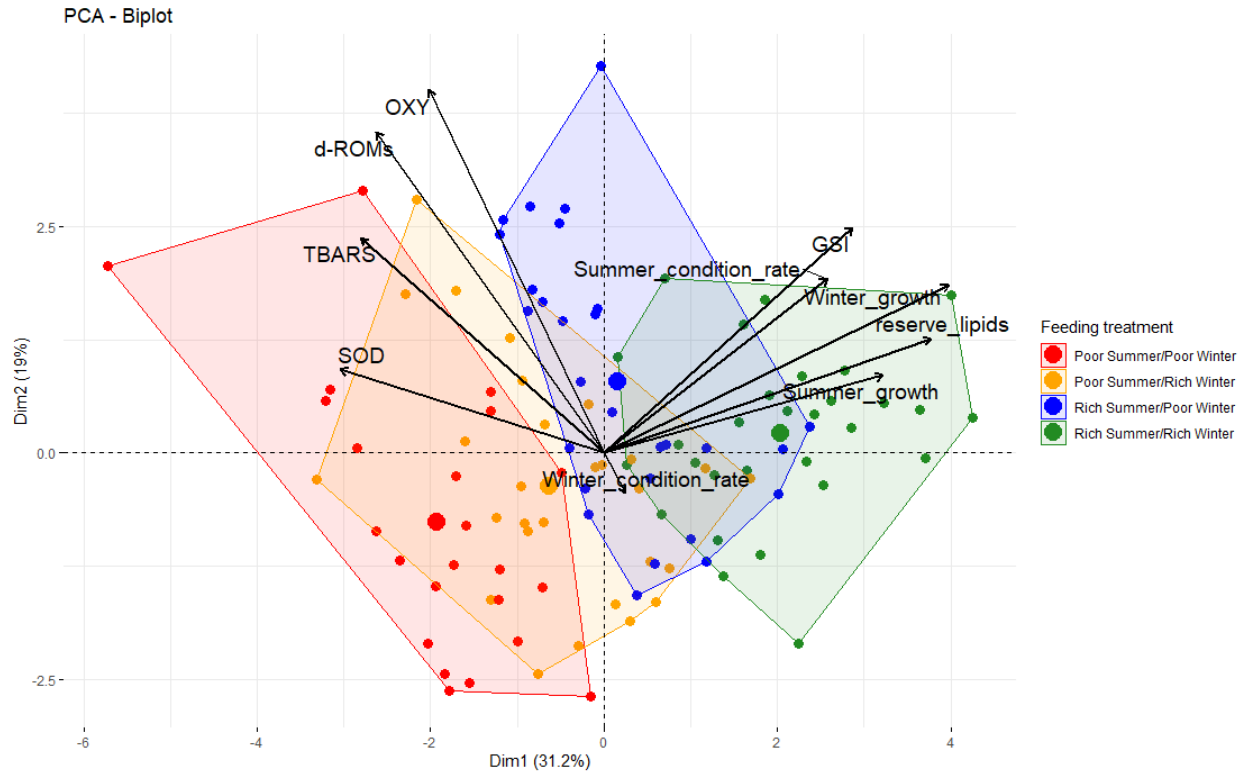
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1022 **Figure 4:** Boxplot of plasma concentrations of OXY (a), SOD (b), d-ROMs (c) and TBARS (d)
1023 for each treatment at the end of the experiment. The number of individuals is indicated under
1024 each boxplot. The outliers are represented by black dots. Treatments with different letters are
1025 significantly different ($P < 0.05$).

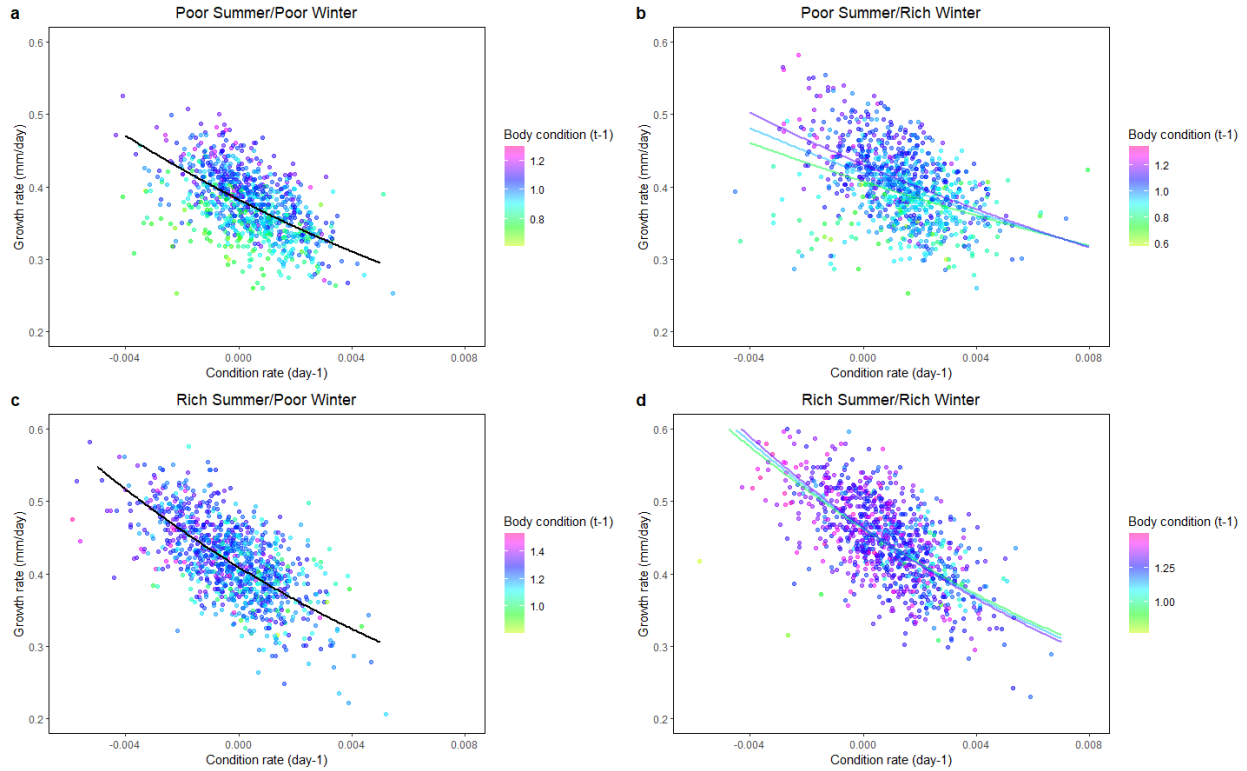
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1028 **Figure 5:** Biplot of the PCA built with summer and winter growth and condition rates,
 1029 antioxidant defense (OXY and SOD), oxidative damage (TBARS and ROM), reserve lipids, and
 1030 GSI. Each point represents an individual. The larger circles represent the barycenter of the
 1031 individuals for a given treatment represented using minimum convex polygon. Note that
 1032 structural lipids have not been included due to their very low variability.

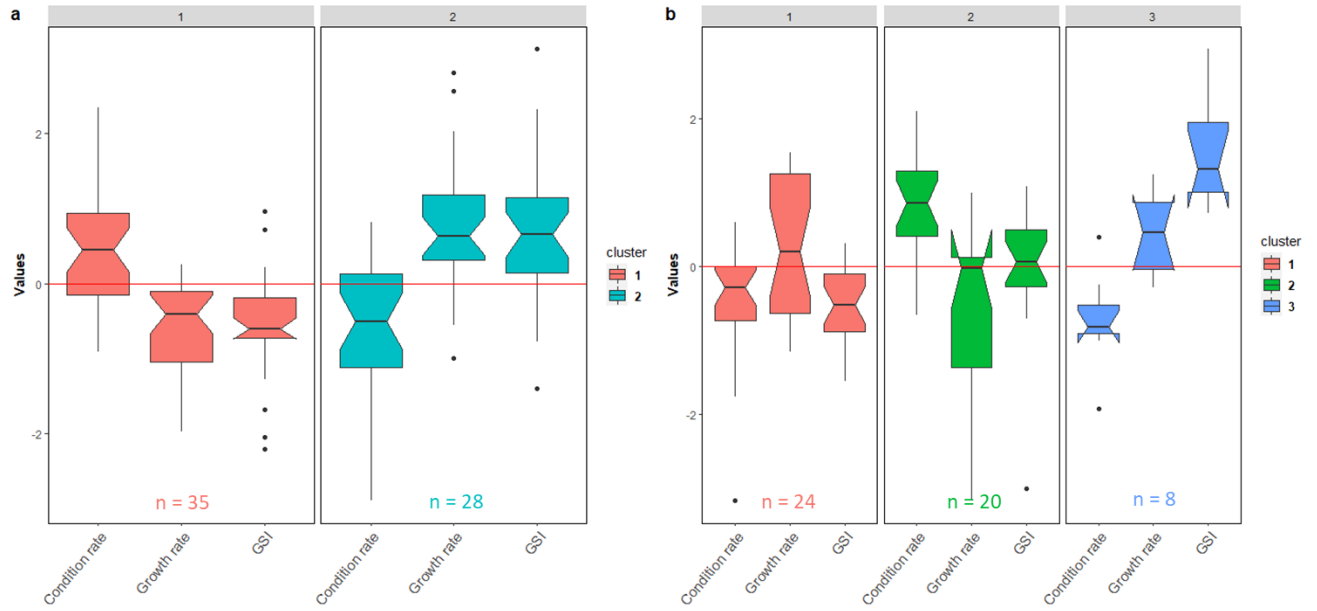
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1035 **Figure 6:** Relationship between growth and body condition rate for the four feeding treatments
 1036 during winter only: Poor Summer/Poor Winter (a), Poor Summer/Rich Winter (b), Rich
 1037 Summer/Poor Winter (c) and Rich Summer/Rich Winter (d). When the interaction between
 1038 condition rate_{t-1} → _t and body condition_{t-1} was significant we represented several prediction lines
 1039 corresponding to the 25%, 50% and 75% quantile of the body condition_{t-1}. If the interaction is
 1040 not significant, only one prediction line (black) is represented corresponding to the median body
 1041 condition _{t-1}.

1042



1043

1044 **Figure 7:** Boxplot of normalized values of body condition rate_{without gonad}, growth rate and GSI for

1045 each cluster for males (a) and females (b). The number of individuals is indicated under each

1046 boxplot. The outliers are represented by black dots.