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## Changes in foraging mode caused by a decline in prey size have major bioenergetic consequences for a small pelagic fish

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35

## 36 **Abstract**

- 37 1. Global warming is causing profound modifications of aquatic ecosystems and one major  
38 outcome appears to be a decline in adult size of many fish species. Over the last decade,  
39 sardine populations in the Gulf of Lions (NW Mediterranean Sea) have shown severe  
40 declines in body size and condition as well as disappearance of the oldest individuals,  
41 which could not be related to overfishing, predation pressure or epizootic diseases.
- 42 2. In this study, we investigated whether this situation reflects a bottom-up phenomenon  
43 caused by reduced size and availability of prey that could lead to energetic constraints.  
44 We fed captive sardines with food items of two different sizes eliciting a change in  
45 feeding mode (filter-feeding on small items and directly capturing larger ones) at two  
46 different rations for several months, and then assessed their muscle bioenergetics to test  
47 for changes in cellular function.
- 48 3. Feeding on smaller items was associated with a decline in body condition, even at high  
49 ration, and almost completely inhibited growth by comparison to sardines fed large  
50 items at high ration.
- 51 4. Sardines fed on small items presented specific mitochondrial adjustments for energy  
52 sparing, indicating a major bioenergetic challenge. Moreover, mitochondria from  
53 sardines in poor condition had low basal oxidative activity but high efficiency of ATP  
54 production. Notably, when body condition was below a threshold value of 1.07, close  
55 to the mean observed in the wild, it was directly correlated with basal mitochondrial  
56 activity in muscle.
- 57 5. The results show a link between whole-animal condition and cellular bioenergetics in

58 the sardine, and reveal physiological consequences of a shift in feeding mode. They  
59 demonstrate that filter-feeding on small prey leads to poor growth, even under abundant  
60 food and an increase in the efficiency of ATP production. These findings may partially  
61 explain the declines in sardine size and condition observed in the wild.

62

63 **Keywords:** Bioenergetics, red muscle, mitochondria, fish shrinking, sardine, foraging  
64 behaviour, food restriction

## 65 **Résumé**

66 Le changement global entraîne de profondes modifications des écosystèmes aquatiques, l'une  
67 des principales étant le déclin de la taille des adultes chez de nombreuses espèces de poissons.  
68 Au cours de la dernière décennie, les populations de sardines du Golfe du Lion (Nord-Ouest de  
69 la Méditerranée) ont montré une importante diminution de leur taille et de leur condition  
70 corporelle ainsi qu'une disparition des individus les plus âgés, qui n'ont pas pu être liées à la  
71 surpêche, à la pression de prédation ou aux épizooties.

72 Dans cette étude, nous avons cherché à savoir si cette situation reflète un phénomène ascendant  
73 causé par la réduction de la taille et de la disponibilité des proies qui pourrait entraîner des  
74 contraintes énergétiques chez la sardine. Nous avons ainsi nourri des sardines captives avec des  
75 granulés de deux tailles différentes provoquant un changement de mode d'alimentation  
76 (filtration des petits granulés et capture directe des plus gros) et à deux rations différentes  
77 pendant plusieurs mois, puis nous avons évalué leur bioénergétique musculaire pour tester les  
78 changements au niveau de leur fonction cellulaire.

79 L'alimentation à base de petits granulés a été associée à un déclin de la condition corporelle,  
80 même à une ration élevée, et à une croissance quasiment inhibée par rapport aux sardines  
81 nourries avec des plus gros granulés à une ration élevée.

82 Les sardines nourries avec des petits granulés ont également présenté des ajustements  
83 mitochondriaux spécifiques pour économiser de l'énergie, indiquant un défi bioénergétique  
84 majeur. De plus, les mitochondries des sardines en mauvaise condition présentaient une faible  
85 activité oxydative basale, mais une efficacité élevée de production d'ATP. Notamment, lorsque  
86 la condition corporelle était inférieure à une valeur seuil de 1,07, proche de la moyenne observée  
87 dans la nature, elle était directement corrélée à l'activité mitochondriale basale dans le muscle.

88 Ces résultats montrent un lien entre la condition de l'animal entier et la bioénergétique cellulaire  
89 chez la sardine, et révèlent les conséquences physiologiques d'un changement de mode  
90 d'alimentation. Ils démontrent que le nourrissage via la filtration de petites proies entraîne une  
91 faible croissance, même en cas de nourriture abondante, et une augmentation de l'efficacité de  
92 la production d'ATP. Ces résultats peuvent expliquer en partie le déclin de la taille et de la  
93 condition des sardines observé dans la nature.

## 94 1. Introduction

95 Marine ecosystems face strong pressures from a combination of climate forcing,  
96 anthropogenic disturbance (pollution, navigation, recreational activities, by-catch, climate  
97 change) and anthropogenic competition for resources (e.g. fisheries) (Halpern *et al.*, 2008), all  
98 of which can impact organismal phenotypes. While water warming and a relaxation of density-  
99 dependence phenomena through fishing should promote an increase in growth rates of  
100 ectothermic organisms (Morrongiello, Sweetman, & Thresher, 2019), there is evidence that the  
101 final adult size of many aquatic ectotherms is declining globally (Daufresne, Lengfellner, &  
102 Sommer, 2009; Forster, Hirst, & Atkinson, 2012). Whereas recently debated (Audzijonyte *et*  
103 *al.*, 2020), this size reduction occurs within and amongst species, throughout the food web,  
104 from top predators (Sibert *et al.*, 2006) to primary producers (Sommer, Paul, & Moustaka-  
105 Gouni, 2015). The decrease in size could result from fishery-induced evolution (as fisheries  
106 targeting mostly larger organisms should favour the selection of slow growth and smaller  
107 phenotypes, Conover & Munch, 2002; Jørgensen *et al.*, 2007) and/or from within-generation  
108 plastic physiological responses. It could also result from direct effects of warming on  
109 physiology (e.g. the temperature-size rule; Atkinson, 1994) or global-change-derived  
110 modifications of primary production (Bopp *et al.*, 2013).

111 There has been a profound decline in size and body condition of sardines *Sardina*  
112 *pilchardus* and anchovies *Engraulis encrasicolus* in the Gulf of Lions (northwestern  
113 Mediterranean Sea), due to lower growth and disappearance of larger and older individuals  
114 (Brosset *et al.*, 2017; Van Beveren *et al.*, 2014). Extensive research has established that this is  
115 not due to top-down effects, such as predation or fishing pressure, nor to pathogens (reviewed  
116 in Saraux *et al.*, 2019). Rather, a bottom-up process appears to be at play, linked to a shift in  
117 plankton communities that the fishes feed upon, towards smaller zooplankton species (Brosset  
118 *et al.*, 2016a; Queiros *et al.*, 2019). When maintained in captivity on artificial feeds, wild

119 sardines exhibited high growth rates and condition, indicating that the decline in size and  
120 condition was a plastic rather than an evolutionary response (Saraux *et al.*, 2019). While it is  
121 obvious that food quantity can have a significant impact on growth and body condition in fishes  
122 (Lee *et al.*, 2018; Sun & Chen, 2009), the potential implications of prey size are less well  
123 known. They deserve to be investigated because of climate-change related regime shifts in food  
124 webs (Garzke, Ismar, & Sommer, 2015). A reduction in prey size is often accompanied by  
125 lower energy content (Zarubin *et al.*, 2014), which may present a major energetic challenge to  
126 predators, even for sardines that are opportunistic planktivores (Palomera *et al.*, 2007; Rumolo  
127 *et al.*, 2016).

128         It has been demonstrated that, for rations of similar energy content, sardines fed small  
129 prey have lower growth and condition than those fed larger prey (Queiros *et al.*, 2019). The  
130 sardine modifies its feeding behaviour with prey size, switching from filter feeding on small  
131 prey to direct capture of larger prey, regardless of prey availability (Costalago, Garrido, &  
132 Palomera, 2015; Garrido *et al.*, 2007). Foraging duration was much higher for sardines fed on  
133 small food items than those fed on larger ones (Queiros *et al.*, 2019). Thus, a possible  
134 mechanism for the poor growth and condition may relate to high energy requirements for  
135 extended swimming activity during filter-feeding, compared to shorter bouts of swimming to  
136 capture large items (Costalago & Palomera, 2014; Crowder, 1985).

137         Foraging behaviour in fishes is sustained by skeletal muscle activity, with the muscles  
138 being structurally separated into discrete slow-twitch oxidative ‘red’ muscle, used for steady  
139 aerobic swimming, and fast-twitch glycolytic ‘white’ muscle, used for short bursts of high-  
140 speed swimming (Bone, 1978; Webb, 1998). Muscular contraction is powered by ATP but, its  
141 production depends on muscle type: while red muscle generates this aerobically by  
142 mitochondrial oxidative phosphorylation using substrates and oxygen delivered in the  
143 bloodstream, white muscle generates ATP mostly through anaerobic glycolysis of intracellular

144 substrates (Fig. 1, Bone, 1978; Webb, 1998). In the sardine, swimming muscle represents up to  
145 70% of body mass and, although the red muscle mass only represents ~10% of the body mass,  
146 its mitochondrial activity accounts for 70% of muscle metabolic activity (Teulier *et al.*, 2019).  
147 Mitochondrial oxidative phosphorylation is a series of reactions that couple substrate oxidation  
148 (catabolism of carbohydrates, lipids or proteins) and oxygen consumption with the generation  
149 of a proton motive force, which is then used by ATP synthase to synthesize ATP (Fig. 1). A  
150 significant proportion of mitochondrial oxygen consumption is not, however, coupled to ATP  
151 synthesis but is used to compensate for proton leakage across the inner mitochondrial  
152 membrane. Mitochondrial proton leak is a ubiquitous waste of potential energy, which reduces  
153 the efficiency of ATP production (*i.e.* the ATP/O ratio) (Brand, 2005; Fig. 1). The ATP/O ratio  
154 defines how much oxygen and nutrients are needed to meet cell ATP demands and, ultimately,  
155 sustain animal performance (Brand, 2005). For instance, mitochondrial ATP/O has been  
156 positively related to muscle performance (Conley *et al.*, 2013; Distefano *et al.*, 2018) and  
157 growth efficiency (Salin *et al.*, 2019; Toyomizu *et al.*, 2011). Mitochondrial efficiency is also  
158 flexible, varying among individuals over time, notably in response to environmental and  
159 physiological constraints such as temperature, oxygen or food availability (Roussel & Voituron,  
160 2020; Salin *et al.*, 2015; Salin *et al.*, 2012; Thorald *et al.*, 2021b). For example, mitochondrial  
161 efficiency can increase to enhance energy conservation during food deprivation (Bourguignon  
162 *et al.*, 2017; Monternier *et al.*, 2017) or decrease to promote heat generation, as in brown  
163 adipose tissue of cold-adapted mammals (Nedergaard & Cannon, 2018). The maintenance of a  
164 high ATP/O ratio and related efficiency may carry significant costs, especially increased  
165 production of reactive oxygen species (Brand, 2000), and/or a decreased carbon flux from  
166 mitochondria that can compromise aspects of cellular biosynthesis (Rolfe & Brand, 1997).  
167 Overall, there is strong evidence that mitochondrial efficiency (ATP/O ratio) can be adjusted

168 plastically, in response to metabolic constraints and energy demands, leading to a dynamic  
169 interplay with the biological condition of an organism (Koch *et al.*, 2021).

170 In this study we investigated whether aerobic muscle energy metabolism and, in  
171 particular, mitochondrial function, might represent a mechanistic nexus for how sardine  
172 foraging mode impacts upon their physical condition (Fig. 1). We thus investigated the  
173 oxidative activity of red muscle fibres and the coupling efficiency of mitochondrial oxidative  
174 phosphorylation in sardines fed for 7 months with either small or large food items (0.1mm and  
175 1.2mm diameter commercial pellets), at either low or high ration (0.3% and 0.6% of fish mass  
176 per day). We predicted that fish fed on small items would show specific mitochondrial  
177 adjustments for energy sparing, with decreased oxygen consumption but enhanced efficiency  
178 (ATP/O ratio), which would indicate that increased metabolic costs of foraging mode  
179 represented an energetic challenge.

180

## 181 **2. Material and methods**

### 182 **2.1 Experimental conditions**

183 All details of the experiment can be found in Queiros *et al.*, 2019. Briefly, wild sardines  
184 were captured off Sète (South of France) in October 2016 and brought back to the Ifremer  
185 Palavas-les-Flots research station. The mean age of sardines was 1.24 years. After acclimation  
186 and weaning onto commercial pellets, sardines were weighed, measured and marked  
187 individually using RFID tags (Biolog-id, Bernay, France). Thereafter, they were distributed  
188 among 8 tanks (vol. 300L, 56-57 sardines per tank) with similar mean ( $\pm$  SD) of mass and length  
189 in each (mass:  $14.1 \pm 3.2$ g; length:  $11.9 \pm 0.7$  cm). A 7-month feeding experiment was  
190 performed, from 14/11/2016 to 15/6/2017, with natural photoperiod and water temperature  
191 (water was pumped directly from the sea). Animals were fed four times a day with commercial  
192 pellets (except on weekends where one daily meal was provided). The experiment included the

193 reproductive season, which occurs once a year between December and March. As detailed in  
194 Queiros *et al.*, 2019, the daily weight gain of sardines *in natura* was 0.2% with good condition  
195 and 0.1% with bad condition. A preliminary study found that these growth rates were achieved  
196 with daily feeding rates of 0.6% and 0.3% of fish mass. Thus, the combination of two pellet  
197 sizes (0.1mm and 1.2mm, within the natural range of sardine prey size) (Le Bourg *et al.*, 2015)  
198 and two rations (0.3% and 0.6% of fish biomass per day) resulted in four treatments: (1) small  
199 items in small quantity (SI-SQ), (2) small items in large quantity (SI-LQ), (3) large items in  
200 small quantity (LI-SQ), (4) large items in large quantity (LI-LQ). The two sizes elicited two  
201 distinct foraging modes, filtration *vs.* particulate capture (Queiros *et al.*, 2019). Each treatment  
202 was randomly assigned to two tanks for replicates. Biometries were performed each month to  
203 correct food quantity against increasing biomass, adjusted each week based on linear  
204 extrapolation of biomass across successive biometries.

205

## 206 **2.2 Sardine sacrifices and morphometric measurements**

207 At the end of the experiment, 1 or 2 sardines were randomly removed from each tank  
208 every day over a period of 1 week, *i.e.* 11 to 12 fish per group, and killed by an overdose of  
209 benzocaine (1000 ppm). Sardines were fasted for 24h before euthanasia. Mass and size of each  
210 sardine were recorded. Intramuscular fat was estimated by fatmeter (Distell Fish Fatmeter  
211 MFM-992, as described in Brosset *et al.*, 2015a) and sex was determined visually. Experiments  
212 were performed in June when sardines were out of the breeding season (Brosset *et al.*, 2016b).  
213 Cumulative growth was estimated based on the increase in size divided by the experiment  
214 duration (mm/day), and the relative growth (in %) was calculated as follows:

$$215 \quad \text{Relative growth} = \frac{\text{Final size} - \text{Initial size}}{\text{Initial size}}$$

216 Where initial and final sizes are expressed in mm.

217 Body condition was calculated following the Le Cren index  $K_n$  as estimated by Brosset  
218 *et al.*, 2015b (based on more than 24,000 wild sardines sampled over the last 50 years):

$$219 \quad K_n = \frac{BM}{0.00607 \times TL^{3.057}}$$

220 where TL is the total length (cm) and BM is the wet body mass (g). This index compares the  
221 actual wet mass of an individual to the mass predicted by the relationship of mass to length for  
222 the entire wild population. As such,  $K_n < 1$  (or  $K_n > 1$ ) means that body condition is lower (or  
223 higher) than the long-term average observed in the wild population

224

### 225 **2.3 Mitochondrial respiration**

226 Oxygen consumption measurements were performed in red muscle at two levels: in  
227 muscle fibres and in isolated mitochondria. At the mitochondrial level, oxygen consumption  
228 was expressed in  $\text{nmol O}\cdot\text{min}^{-1}\cdot\text{mg}^{-1}$  of protein, and it was expressed in  $\text{nmol O}\cdot\text{min}^{-1}\cdot\text{mg}^{-1}$  of  
229 red muscle at the fibre level. The oxygen consumption was then estimated at the muscle level  
230 by multiplying the oxygen consumption obtained at the fibre level by the red muscle mass  
231 ( $\mu\text{mol O}\cdot\text{min}^{-1}$ ) or by the relative red muscle mass ( $\text{nmol O}\cdot\text{min}^{-1}\cdot\text{g}^{-1}$  of fish) (see Table 2).

232

#### 233 **2.3.a Red muscle fibre preparation and oxidative activity**

234 After dissection, the total mass of red muscle was measured and a ~5 mg sample of  
235 fibres was withdrawn (Fig. 1). Fibre respiration was monitored at 20°C using high resolution  
236 respirometers (Oxygraph-2K, Oroboros® Instruments – WGT Austria) in air-saturated  
237 respiration buffer (Mir05: 110 mM sucrose, 0.5 mM EGTA, 3 mM  $\text{MgCl}_2$ , 60 mM K-  
238 lactobionate, 20 mM taurine, 10 mM  $\text{KH}_2\text{PO}_4$ , 1 g/L fatty acid-free bovine serum albumin and  
239 20 mM HEPES, pH 7.1) using different combination of respiratory substrates (5 mM  
240 glutamate/2.5 mM malate; 40  $\mu\text{M}$  palmitoyl-carnitine/2.5 mM malate; 5 mM pyruvate/2.5 mM  
241 malate/5 mM succinate) with a protocol adapted from Teulier *et al.*, 2019. These different

242 combinations of substrates enabled us to assay mitochondrial respiration using substrates  
243 derived from amino acid (glutamate), carbohydrate (pyruvate) and lipid (palmitoyl-carnitine)  
244 metabolic pathways. In addition, the mixture of NADH- and FADH<sub>2</sub>-linked substrates  
245 (pyruvate/malate and succinate) allowed a full activation of mitochondrial oxidative activity by  
246 providing electrons to complex I and complex II of the electron transport system (ETS).  
247 Phosphorylating respiration was then initiated by adding 1mM ADP, and the integrity of  
248 mitochondria within muscle fibres was subsequently tested by adding 10µM cytochrome c.  
249 Finally, a sequential addition of 1 µM p-trifluoromethoxy-carbonyl-cyanide-phenyl hydrazine  
250 (FCCP) was performed to measure maximal respiratory activity of the fibres.

251

### 252 ***2.3.b Mitochondrial isolation, coupling efficiency, respiratory capacity and content***

253 Mitochondria were isolated from red skeletal muscle in an ice-cold isolation buffer  
254 containing (100 mM sucrose, 50 mM KCl, 5 mM EDTA, 50 mM Tris-base, pH 7.4 at 4°C),  
255 according to previously described protocol for small tissue samples (Boël *et al.*, 2019),  
256 involving potter homogenizer, partial protease digestion, and differential centrifugation with  
257 mitochondria pelleted at 9000 × g, all steps at 4°C. Protein content of the preparation was  
258 assayed in duplicate at 540nm using the biuret method, with bovine serum albumin as standard  
259 (Gornall *et al.*, 1949). Absorbance of the same volume of mitochondria was also assayed at  
260 540nm in a solution containing 0.6% Na-K-tartrate and 3% NaOH and subtracted, to correct  
261 for any contamination with pigments absorbing at 540nm.

262 Mitochondrial oxidative phosphorylation efficiency was assessed at 20°C by measuring  
263 the rates of ATP synthesis and oxygen consumption in respiratory buffer (120 mM KCl, 5 mM  
264 KH<sub>2</sub>PO<sub>4</sub>, 1 mM EGTA, 2 mM MgCl<sub>2</sub>, 0.3% fatty acid-free bovine serum albumin (w/v), and  
265 3mM HEPES, pH 7.4) supplemented with 20 mM glucose, 1.5 U/mL hexokinase (Colinet,  
266 Renault, & Roussel, 2017; Teulier *et al.*, 2010). Mitochondria were energized with a mixture

267 of 5 mM pyruvate, 2.5 mM malate, 5 mM succinate to fully activate the ETS. ADP (500  $\mu$ M)  
268 was added to initiate ATP synthesis. After recording the phosphorylating respiration rate using  
269 a Clark electrode (Rank Brother Ltd, Cambridge, UK), four 100  $\mu$ L samples of mitochondrial  
270 suspension were withdrawn from the respiratory chamber every 2 min and immediately  
271 quenched in 100 $\mu$ L of ice-cold perchloric acid solution (10% HClO<sub>4</sub> and 25mM EDTA).  
272 Production of ATP was determined from the slope of the linear accumulation of glucose-6-  
273 phosphate content over the sampling time interval (6 min) as described previously (Colinet *et*  
274 *al.*, 2017; Teulier *et al.*, 2010). To make sure that ATP synthesis rate was specific to  
275 mitochondrial ATP synthase activity, we determined oxygen consumption and ATP synthesis  
276 rates in the presence of oligomycin (1 $\mu$ g/mL) that inhibits mitochondrial ATP synthase. These  
277 values were taken into account (*i.e.* subtracted from the raw ATP synthesis) to calculate the rate  
278 of mitochondrial ATP synthesis (Teulier *et al.*, 2010). Of note, the basal non-phosphorylating  
279 oxygen consumption recorded in the presence of oligomycin is a measure of the maximal rate  
280 of proton leak across the inner membrane of mitochondria. Due to the linear relationship  
281 between ATP synthesis and oxygen consumption in isolated mitochondria from different tissues  
282 and organisms (Beavis & Lehninger, 1986; Fontaine *et al.*, 1996; Nogueira *et al.*, 2002; Roussel  
283 *et al.*, 2015; Teulier *et al.*, 2010), we presented these data on a single graph by drawing a linear  
284 relationship between the basal non-phosphorylating oxygen consumption activity and the  
285 maximal oxidative phosphorylation activity, which is related to maximal rates of oxygen  
286 consumption and corresponding ATP synthesis (Fig. 1B).

287 Maximal activity of the electron transport system (*i.e.* the respiratory capacity) was  
288 measured at 20°C by adding 2  $\mu$ M FCCP in the respiratory buffer supplemented with 5mM  
289 pyruvate, 2.5 mM malate, 5 mM succinate, and 1  $\mu$ g/mL oligomycin. Mitochondrial content of  
290 skeletal muscle was estimated from the ratio between the maximal oxygen consumption rates

291 of muscle fibres (expressed per gram of muscle) and mitochondria (expressed per milligram of  
292 protein).

293

## 294 **2.5. Statistical analyses**

295 Linear mixed-models (LMM) were used to evaluate the effects of food size and quantity  
296 on phenotypic traits, red muscle mitochondrial respiration and efficiency. These models all  
297 followed a similar structure, with food size and quantity as well as their interaction as fixed  
298 effects, while sex was included as a random effect to remove any potential bias associated to  
299 differences between males and females. When an interaction between size and quantity of items  
300 was significant ( $P < 0.05$ ) or tended to be significant ( $P < 0.07$ ), post-hoc tests comparing all  
301 four treatments (*lsmeans*) were performed. When the interaction was not significant, it was  
302 removed from the model and the p- values obtained in the simplified model were reported in  
303 the results section.

304 The relationship between individual body condition and basal mitochondrial respiration  
305 was analysed by piecewise linear regression (Fig. 3). Once the breakpoint was estimated, linear  
306 regressions were evaluated over each segment of condition (*i.e.* before and after the breakpoint).

307 Data are presented as means  $\pm$  SE. Sample sizes varied among models because some  
308 data were missing for some fish, or at the fibre level, data were removed from analyses if  
309 addition of cytochrome c caused oxygen consumption to increase by 30% or more (see 2.3.a).  
310 Statistical analyses were performed in *R* v. 3.6.1. with the packages *lme4* and *lsmeans*.

311

## 312 **3. Results**

### 313 **3.1. Effect of food size and quantity on body condition and growth**

314 For the effect of food size and quantity on body condition, fat content, growth and final  
315 mass, the interaction between size and quantity was always significant or close to significance

316 (LMMs:  $P = 0.025-0.061$ ). LI-LQ sardines showed the highest body condition, fat content, body  
317 mass, cumulative and relative growth compared to the other three groups (post-hoc lsmeans:  $P$   
318  $< 0.010$ ), while LI-SQ, SI-LQ and SI-SQ did not differ significantly (Table 1). By contrast,  
319 there was no interaction between food size and quantity for effects on red muscle mass, whether  
320 in absolute terms ( $F = 2.359$ ;  $P = 0.133$ ,  $n = 9$ ) or relative to body mass ( $F = 0.002$ ;  $P = 0.962$ ,  
321  $n = 9$ ). Still, LI sardines had greater absolute red muscle mass than SI sardines ( $F = 15.152$ ;  $P$   
322  $< 0.001$ ), as did LQ compared to SQ sardines ( $F = 4.551$ ;  $P = 0.039$ ). Finally, the size of items  
323 also had an effect on relative red muscle mass ( $F = 16.515$ ;  $P < 0.001$ ) with LI sardines being  
324 higher than SI (Table 1).

325

### 326 **3.2. Oxidative metabolism at different levels of organisation**

327 The phosphorylating respiration state of skeletal muscle fibres obtained with different  
328 substrates is presented in Supplementary Material (Figure S1). Apart from glutamate/malate,  
329 there was no effect of food size, quantity or their interaction on the phosphorylating state of  
330 fibres (all  $P > 0.05$ ). Regarding glutamate/malate, the interaction between food size and quantity  
331 tended to be significant ( $F = 3.614$ ,  $P = 0.066$ ), and muscle phosphorylating respiration was  
332 affected by food size ( $F = 4.220$ ,  $P = 0.048$ , post-hoc tests: SI-LQ  $<$  LI-LQ,  $P = 0.040$ ).

333 Table 2 reports the maximal respiration state following addition of FCCP, as measured  
334 in isolated mitochondria and muscle fibres, and further estimated in whole red muscle and fish.  
335 Maximal respiration of isolated mitochondria was only affected by food size ( $F = 9.334$ ;  $P =$   
336  $0.004$ ), and was significantly higher in LI than in SI sardines (Table 2). Similarly, mitochondrial  
337 content was only affected by food size ( $F = 4.604$ ;  $P = 0.040$ ) but in an opposite direction, being  
338 significantly lower in LI groups. The interaction between food size and quantity was close to  
339 significance ( $F = 3.228$ ;  $P = 0.082$ ), suggesting that the negative effect of food size on  
340 mitochondrial content was mostly observed in sardines fed in small quantity. At the fibre level,

341 while the interaction between food size and quantity was significant for the maximal respiration  
342 state measured at this level ( $F = 6.697$ ;  $P = 0.014$ ), no differences in fibre respiration were  
343 highlighted among groups. Finally, the food treatments had no effect on maximal respiration  
344 rates at the red muscle or whole fish level ( $P > 0.05$  for size, quantity, and its interaction).

345

### 346 **3.3. Mitochondrial oxidative phosphorylation efficiency**

347 At the mitochondrial level, there was no interaction between food size and quantity on  
348 oxidative phosphorylation activity (*i.e.* the rates of oxygen consumption and associated ATP  
349 synthesis). However, activity was higher in sardines fed large food items (oxygen consumption:  
350  $F = 9.807$ ;  $P = 0.003$ ; ATP production:  $F = 10.638$ ;  $P = 0.002$ ), regardless of quantity ( $P > 0.05$ ,  
351 Fig. 2A). Basal non-phosphorylating respiration state measured in the presence of oligomycin  
352 (*i.e.* the intercept with the x-axis) was also significantly higher in LI sardines ( $F = 11.746$ ;  $P =$   
353  $0.002$ , see box in Fig. 2A). There was no significant interaction of size and quantity, and no  
354 effect of size or quantity on the slopes of the relationships between rates of ATP synthesis and  
355 oxygen consumption (Size\*Quantity:  $F = 0.014$ ;  $P = 0.906$ ; Size:  $F = 0.784$ ;  $P = 0.382$ ;  
356 Quantity:  $F = 2.017$ ;  $P = 0.164$ ). Thus, these slopes were similar between SI and LI sardines  
357 (Slope<sub>SI</sub>:  $3.19 \pm 0.15$ ; Slope<sub>LI</sub>:  $3.03 \pm 0.10$ ). Altogether, these results indicate that the  
358 regression line relating ATP synthesis to oxygen consumption was shifted to the right in LI  
359 compared to SI groups, meaning that mitochondria from LI sardines had to consume more  
360 oxygen to produce the same amount of ATP, due to a higher basal non-phosphorylating  
361 respiration or “leak” respiration (Fig. 2A).

362 When mitochondrial function was quantified for the entire red muscle, oxidative  
363 phosphorylation activity did not differ among treatments except for LI-LQ sardines, which  
364 exhibited higher rates of ATP synthesis and corresponding phosphorylating respiration, and  
365 higher basal non-phosphorylating respiration than the other groups ( $P < 0.05$ , Fig. 2B).

366 However, as the slopes were similar between LI-LQ and the other groups (Slope<sub>LI-LQ</sub>:  $3.17 \pm$   
367  $0.19$ ; Slope<sub>other groups</sub>:  $2.96 \pm 0.18$ ;  $P > 0.05$ ), red muscles of LI-LQ sardines needed to consume  
368 more oxygen to produce the same amount of ATP compared to the sardines from the other three  
369 groups (Fig. 2B).

370

### 371 **3.4. Basal respiration in relation to body condition**

372 The rate of basal non-phosphorylating respiration at the mitochondrial level was  
373 significantly related to Le Cren body condition (Fig. 3). The segmented regression analysis  
374 showed a significant increase in basal non-phosphorylating respiration rate with body  
375 condition, until a condition threshold of 1.07 ( $R^2 = 0.45$ ;  $P < 0.001$ ) beyond which no significant  
376 relation was found ( $P > 0.05$ , Fig. 3).

377

## 378 **4. Discussion**

379 The results demonstrate clear links between sardine red muscle energetics and foraging  
380 modes, indicating effects of both food size and ration. Reducing the size and/or quantity of food  
381 led to a series of mitochondrial energy sparing mechanisms (decrease in maximum oxygen  
382 consumption and ATP production, enhanced ATP production efficiency and reduced waste of  
383 oxygen linked to proton leak), presumably to maintain energy homeostasis. Such energy saving  
384 processes suggest that sardines feeding on small food items or small food quantities faced an  
385 energetic challenge. These metabolic processes were linked across different levels, from  
386 macroscopic integrative traits such as body mass and body condition to intracellular  
387 mechanisms such as mitochondrial efficiency. The effects of food ration were stronger at the  
388 whole animal level than at the tissue or mitochondrial level, whereas food size also induced  
389 marked mitochondrial adjustments beyond the effects at tissue or whole animal scale (Fig. 4).  
390 This shows that energy saving processes were not adequate to counteract detrimental effects of

391 foraging on small particles. Indeed, despite an enhanced mitochondrial efficiency to produce  
392 ATP, SI sardines still exhibited lower body condition, body mass and growth performance,  
393 regardless of the ration provided (Queiros *et al.*, 2019). Our results therefore support the  
394 hypothesis that filter-feeding behaviour is more costly than particulate-feeding in  
395 Mediterranean sardines (Queiros *et al.*, 2019), unlike in other small pelagic species (Gibson &  
396 Ezzi, 1992; Sanderson & Cech, 1992; Van Der Lingen, 1995), and that this induces plastic  
397 responses in cellular energetics.

398

#### 399 **4.1. Food size induces subcellular bioenergetic adjustments.**

400         Why would the size of food items affect traits like body condition, body mass or growth  
401 performance? Part of the answer may reside in the most striking result of our study, which is  
402 that small food items triggered bioenergetic adjustments in sardine muscle mitochondria. The  
403 effects of food size overwhelmed any potential effect of quantity. Small food items may have  
404 induced an increased utilisation of lipids, as intramuscular lipids were ~50% lower in SI-SQ  
405 compared to LI-LQ sardines. Moreover, a reduction in glutamate oxidation is a known protein-  
406 sparing mechanism, which suggests that protein catabolism may have been occurring. This,  
407 together, may explain why SI sardine exhibited lower red muscle mass both in absolute and  
408 relative terms.

409         Feeding on small food items was also associated with decreased oxidative capacity and  
410 reduced energy (ATP) outflow, from mitochondria up to whole muscle. This involved a severe  
411 loss of mitochondrial power, *i.e.* a ~50% decrease in both maximal rates of ATP synthesis and  
412 oxygen consumption. These reduced maximal rates were balanced by a higher coupling  
413 efficiency; mitochondria of SI sardines consumed less oxygen than LI sardines to produce a  
414 given amount of ATP. The lower maximal respiratory capacity of skeletal muscle and economic  
415 management of cellular resources are energy saving mechanisms, decreasing the quantity of

416 substrates required to produce ATP. Similar adjustments have been reported in skeletal muscle  
417 of birds at a critical stage of fasting, when endogenous lipid stores are depleted (Bourguignon  
418 *et al.*, 2017; Monternier *et al.*, 2017), and also in skeletal muscle of mammals fed on protein-  
419 deficient diets (Zangarelli *et al.*, 2006). Overall, these results indicate that mitochondrial  
420 efficiency improves when energy balance is severely threatened in the sardine. Consequently,  
421 our results indicate that sardines were unable to cope with the high energy expenditure imposed  
422 by filter-feeding on small items, even when these were provided at high ration.

423

#### 424 **4.2. Food quantity mainly influenced the whole organism.**

425 It is well established that food shortage triggers adaptive behavioural, physiological and  
426 cellular responses to lower costs of living, reducing metabolic rates, spontaneous activity and  
427 somatic growth (Metcalf, Van Leeuwen, & Killen, 2016). For example, the standard metabolic  
428 rate of juvenile brown trout *Salmo trutta* changes as a function of food availability, decreasing  
429 or increasing when fish are fed on a low or high ration, respectively (Auer *et al.*, 2016), which  
430 was closely related to their growth rate (Auer *et al.*, 2015). In our study, a 50% reduction in  
431 ration negatively impacted body condition (-26%), body mass (-33%) and dramatically slowed  
432 growth rate of LI sardines (-64%, similarly to what Queiros *et al.*, 2019 found). While a similar  
433 trend was observed for growth rate in SI sardines when comparing between rations (-68%) the  
434 difference was not significant, presumably because the energetic challenge of foraging on small  
435 items transcended any effect of ration (Table 1).

436 Energy conservation during food shortage is also enacted at a cellular level, by  
437 reductions in energy demanding processes and oxidative activity of metabolically active tissues,  
438 such as liver and skeletal muscles (McCue, 2010). For instance, the oxidative activity of brown  
439 trout muscle is positively correlated with food intake and maximum metabolic rate (Salin *et al.*,  
440 2016a; 2016b). In the sardines, bioenergetics of whole red muscle in the LI group was positively

441 correlated with food availability, which is likely due to muscle mass. Because of lower body  
442 mass and red muscle mass in food-restricted fish, maximal oxygen consumption and ATP  
443 synthesis rates of the muscle are depressed. Down regulation of aerobic metabolic pathways  
444 has been reported in the red muscle of food-restricted gilthead sea bream *Sparus aurata*  
445 (Bermejo-Nogales *et al.*, 2011).

446         The lowered respiratory capacity of whole muscle in LI-SQ sardines appears mainly to  
447 be due to decreased mitochondrial content rather than to changes in mitochondrial activity or  
448 skeletal muscle protein content. Changes in mitochondrial content could be caused by  
449 dysregulation of autophagy and biogenesis. The former could be induced by caloric restriction  
450 (reviewed in Mehrabani *et al.*, 2020) while the latter, which is extremely costly, is probably  
451 inhibited to conserve energy. It is also possible that the decrease in mitochondrial content and  
452 associated loss of metabolic power in the sardines is linked to decreased use of slow-twitch  
453 aerobic red muscle for a particulate capture feeding mode (Hood, 2009; Novak *et al.*, 2005), as  
454 prey capture tends to use fast-twitch anaerobic white muscle (Bone, 1978).

455

#### 456 **4.3. Body condition index and skeletal muscle mitochondria.**

457         The energetic constraints associated with the filtering mode led to very low body  
458 condition in the sardines. It is fascinating that, below a threshold value of 1.07, declines in body  
459 condition index were strongly correlated with declines in basal non-phosphorylating respiration  
460 rate of muscle mitochondria. This threshold is surprisingly close to the mean body condition of  
461 sardines observed in the wild, around 1 (Brosset *et al.*, 2015b), which may imply that wild  
462 populations are also at a threshold of bioenergetic disequilibrium. Basal non-phosphorylating  
463 respiration represents maximal proton leakage across the inner mitochondrial membrane.  
464 Limiting proton leak lowers costs of basal maintenance (Boutilier & St-Pierre, 2002) but may  
465 carry an oxidative risk, such as an increased reactive oxygen species production (Salin *et al.*,

466 2018). A reduction of maintenance costs could also be achieved by decreasing mitochondrial  
467 content (Guderley, 2004), as observed in LI-SQ sardines (Fig 2b). That is, a decrease in  
468 mitochondrial content seems less harmful than directly reducing basal respiration rate itself, as  
469 LI-SQ body condition stayed closer to 1 than the SI groups.

470 Hence, the decline in mitochondrial energy wastage in sardines with poor condition  
471 suggests that modifying mitochondrial function provides an economical phenotype when  
472 metabolic costs of foraging are high compared to energy acquired.

473

#### 474 **4.4. Conclusions**

475 Within our experimental conditions, we provide clear evidence that, in sardines, feeding  
476 on small prey can present a greater energetic challenge than reduced availability of large prey.  
477 Feeding sardines a restricted ration of large food items reduced their body condition, growth  
478 rate and body mass, revealing an unbalanced energy budget, but did not stimulate plastic  
479 metabolic responses within mitochondria. By contrast, feeding small items, whatever the  
480 quantity, induced energy-saving adjustments in mitochondria that are typical of a severe  
481 energetic challenge (Bourguignon *et al.*, 2017; Costalago & Palomera, 2014). The food size  
482 effect seems to be mediated by feeding mode in the sardines, with the switch from prey capture  
483 to filtering. Therefore, impacts of prey size on population condition could be profoundly non-  
484 linear. Prey size might only have minor influence on condition as long as sardines use a capture  
485 feeding mode, but when prey species are small enough to trigger a change to filtering mode,  
486 there are dramatic consequences for body condition.

487 While this study focuses on sardines in the north-western Mediterranean Sea, it may be  
488 indicative of a widespread phenomenon linked to climate change. That is, if global warming  
489 causes systematic reductions in prey size (Daufresne *et al.*, 2009), the extra time and energy  
490 required to forage could cause energy challenges at multiple levels of the food web. Coupled

491 with increased metabolic demands of ectotherms in a warmer environment, this could lead to  
492 reduced growth rates and be a major contributor to declining final adult sizes in fishes (Gardner  
493 *et al.*, 2011).

494

## 495 **References**

- 496 Atkinson, D. (1994). Temperature and Organism Size-A Law for Ectotherms? *Advances in*  
497 *Ecological Research*, 25, 1–58.
- 498 Audzijonyte, A., Richards, S. A., Stuart-Smith, R. D., Pecl, G., Edgar, G. J., Barrett, N. S., ...  
499 Blanchard, J. L. (2020). Fish body sizes change with temperature but not all species  
500 shrink with warming. *Nature Ecology and Evolution*, 4(6), 809–814. doi:  
501 10.1038/s41559-020-1171-0
- 502 Auer, S. K., Salin, K., Rudolf, A. M., Anderson, G. J., & Metcalfe, N. B. (2015). Flexibility in  
503 metabolic rate confers a growth advantage under changing food availability. *Journal of*  
504 *Animal Ecology*, 84(5), 1405–1411. doi: 10.1111/1365-2656.12384
- 505 Auer, S. K., Salin, K., Rudolf, A. M., Anderson, G. J., & Metcalfe, N. B. (2016). Differential  
506 effects of food availability on minimum and maximum rates of metabolism. *Biology*  
507 *Letters*, 12(10), 0–4. doi: 10.1098/rsbl.2016.0586
- 508 Beavis, A. D., & Lehninger, A. L. (1986). The upper and lower limits of the mechanistic  
509 stoichiometry of mitochondrial oxidative phosphorylation: Stoichiometry of oxidative  
510 phosphorylation. *European Journal of Biochemistry*, 158(2), 315–322. doi:  
511 10.1111/j.1432-1033.1986.tb09753.x
- 512 Bermejo-Nogales, A., Benedito-Palos, L., Calduch-Giner, J. A., & Pérez-Sánchez, J. (2011).  
513 Feed restriction up-regulates uncoupling protein 3 (UCP3) gene expression in heart and  
514 red muscle tissues of gilthead sea bream (*Sparus aurata* L.). New insights in substrate  
515 oxidation and energy expenditure. *Comparative Biochemistry and Physiology - A*  
516 *Molecular and Integrative Physiology*, 159(3), 296–302. doi:  
517 10.1016/j.cbpa.2011.03.024
- 518 Boël, M., Romestaing, C., Voituron, Y., & Roussel, D. (2019). Allometry of mitochondrial  
519 efficiency is set by metabolic intensity. *Proceedings of the Royal Society B: Biological*  
520 *Sciences*, 286(1911). doi: 10.1098/rspb.2019.1693
- 521 Bone, Q. (1978). *Locomotor Muscle* (Vol. 7). Academic Press. doi: 10.1007/BF00007710
- 522 Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., ... Vichi, M.  
523 (2013). Multiple stressors of ocean ecosystems in the 21st century: Projections with  
524 CMIP5 models. *Biogeosciences*, 10(10), 6225–6245. doi: 10.5194/bg-10-6225-2013
- 525 Bourguignon, A., Rameau, A., Toullec, G., Romestaing, C., & Roussel, D. (2017). Increased  
526 mitochondrial energy efficiency in skeletal muscle after long-term fasting: Its relevance  
527 to animal performance. *Journal of Experimental Biology*, 220(13), 2445–2451. doi:  
528 10.1242/jeb.159087
- 529 Boutilier, R. G., & St-Pierre, J. (2002). Adaptive plasticity of skeletal muscle energetics in

- 530 hibernating frogs: Mitochondrial proton leak during metabolic depression. *Journal of*  
531 *Experimental Biology*, 205(15), 2287–2296.
- 532 Brand, M. (2005). The efficiency and plasticity of mitochondrial energy transduction.  
533 *Biochemical Society Transactions*, 33(5), 897–904. doi: 10.1042/BST20050897
- 534 Brand, M. D. (2000). Uncoupling to survive? The role of mitochondrial inefficiency in  
535 ageing. *Experimental Gerontology*, 35(6), 811–820. doi: [https://doi.org/10.1016/S0531-](https://doi.org/10.1016/S0531-5565(00)00135-2)  
536 5565(00)00135-2
- 537 Brosset, P., Fromentin, J. M., Ménard, F., Pernet, F., Bourdeix, J. H., Bigot, J. L., ... Saraux,  
538 C. (2015a). Measurement and analysis of small pelagic fish condition: A suitable method  
539 for rapid evaluation in the field. *Journal of Experimental Marine Biology and Ecology*,  
540 462, 90–97. doi: 10.1016/j.jembe.2014.10.016
- 541 Brosset, P., Fromentin, J. M., Van Beveren, E., Lloret, J., Marques, V., Basilone, G., ...  
542 Saraux, C. (2017). Spatio-temporal patterns and environmental controls of small pelagic  
543 fish body condition from contrasted Mediterranean areas. *Progress in Oceanography*,  
544 151, 149–162. doi: 10.1016/j.pocean.2016.12.002
- 545 Brosset, P., Le Bourg, B., Costalago, D., BĂnaru, D., Van Beveren, E., Bourdeix, J. H., ...  
546 Saraux, C. (2016a). Linking small pelagic dietary shifts with ecosystem changes in the  
547 Gulf of Lions. *Marine Ecology Progress Series*, 554, 157–171. doi: 10.3354/meps11796
- 548 Brosset, P., Lloret, J., Muñoz, M., Fauvel, C., Van Beveren, E., Marques, V., ... Saraux, C.  
549 (2016b). Body reserves mediate trade-offs between life-history traits: New insights from  
550 small pelagic fish reproduction. *Royal Society Open Science*, 3(10). doi:  
551 10.1098/rsos.160202
- 552 Brosset, P., Ménard, F., Fromentin, J. M., Bonhommeau, S., Ulses, C., Bourdeix, J. H., ...  
553 Saraux, C. (2015b). Influence of environmental variability and age on the body condition  
554 of small pelagic fish in the Gulf of Lions. *Marine Ecology Progress Series*, 529, 219–  
555 231. doi: 10.3354/meps11275
- 556 Colinet, H., Renault, D., & Roussel, D. (2017). Cold acclimation allows *Drosophila* flies to  
557 maintain mitochondrial functioning under cold stress. *Insect Biochemistry and Molecular*  
558 *Biology*, 80, 52–60. doi: 10.1016/j.ibmb.2016.11.007
- 559 Conley, K. E., Jubrias, S. A., Cress, M. E., & Esselman, P. (2013). Exercise efficiency is  
560 reduced by mitochondrial uncoupling in the elderly. *Experimental Physiology*, 98(3),  
561 768–777. doi: 10.1113/expphysiol.2012.067314
- 562 Conover, D. O., & Munch, S. B. (2002). Sustaining fisheries yields over evolutionary time  
563 scales. *Science*, 297(5578), 94–96. doi: 10.1126/science.1074085
- 564 Costalago, D., Garrido, S., & Palomera, I. (2015). Comparison of the feeding apparatus and  
565 diet of European sardines *Sardina pilchardus* of Atlantic and Mediterranean waters:  
566 Ecological implications. *Journal of Fish Biology*, 86(4), 1348–1362. doi:  
567 10.1111/jfb.12645
- 568 Costalago, D., & Palomera, I. (2014). Feeding of European pilchard (*Sardina pilchardus*) in  
569 the northwestern Mediterranean: from late larvae to adults. *Scientia Marina*, 78(1), 41–  
570 54. doi: 10.3989/scimar.03898.06d
- 571 Crowder, L. B. (1985). Optimal foraging and feeding mode shifts in fishes. *Environmental*  
572 *Biology of Fishes*, 12(1), 57–62. doi: 10.1007/BF00007710

- 573 Daufresne, M., Lengfellner, K., & Sommer, U. (2009). Global warming benefits the small in  
574 aquatic ecosystems. *Proceedings of the National Academy of Sciences of the United*  
575 *States of America*, 106(31), 12788–12793. doi: 10.1073/pnas.0902080106
- 576 Distefano, G., Standley, R. A., Zhang, X., Carnero, E. A., Yi, F., Cornell, H. H., & Coen, P.  
577 M. (2018). Physical activity unveils the relationship between mitochondrial energetics,  
578 muscle quality, and physical function in older adults. *Journal of Cachexia, Sarcopenia*  
579 *and Muscle*, 9(2), 279–294. doi: 10.1002/jcsm.12272
- 580 Fontaine, E. M., Moussa, M., Devin, A., Garcia, J., Ghisolfi, J., Rigoulet, M., & Leverve, X.  
581 M. (1996). Effect of polyunsaturated fatty acids deficiency on oxidative phosphorylation  
582 in rat liver mitochondria. *Biochimica et Biophysica Acta - Bioenergetics*, 1276(3), 181–  
583 187. doi: 10.1016/0005-2728(96)00075-8
- 584 Forster, J., Hirst, A. G., & Atkinson, D. (2012). Warming-induced reductions in body size are  
585 greater in aquatic than terrestrial species. *Proceedings of the National Academy of*  
586 *Sciences of the United States of America*, 109(47), 19310–19314. doi:  
587 10.1073/pnas.1210460109
- 588 Gardner, J. L., Peters, A., Kearney, M. R., Joseph, L., & Heinsohn, R. (2011). Declining body  
589 size: A third universal response to warming? *Trends in Ecology and Evolution*, 26(6),  
590 285–291. doi: 10.1016/j.tree.2011.03.005
- 591 Garrido, S., Marçalo, A., Zwolinski, J., & Van Der Lingen, C. D. (2007). Laboratory  
592 investigations on the effect of prey size and concentration on the feeding behaviour of  
593 *Sardina pilchardus*. *Marine Ecology Progress Series*, 330, 189–199. doi:  
594 10.3354/meps330189
- 595 Garzke, J., Ismar, S. M. H., & Sommer, U. (2015). Climate change affects low trophic level  
596 marine consumers: warming decreases copepod size and abundance. *Oecologia*, 177(3),  
597 849–860. doi: 10.1007/s00442-014-3130-4
- 598 Gibson, R. N., & Ezzi, I. A. (1992). The relative profitability of particulate- and filter-feeding  
599 in the herring, *Clupea harengus* L. *Journal of Fish Biology*, 40(4), 577–590. doi:  
600 10.1111/j.1095-8649.1992.tb02607.x
- 601 Gornall, A. G., Bardawill, C. J., & David, M. M. (1949). Determination of serum proteins by  
602 means of the biuret reaction. *The Journal of Biological Chemistry*, 177(2), 751–766.
- 603 Guderley, H. (2004). Metabolic responses to low temperature in fish muscle. *Biological*  
604 *Reviews of the Cambridge Philosophical Society*, 79(2), 409–427. doi:  
605 10.1017/S1464793103006328
- 606 Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., ...  
607 Watson, R. (2008). A Global Map of Human Impact on cadherin-mediated cell adhesion  
608 in metazoans may reflect the co-option of a class of proteins whose earliest function was  
609 to interpret and re- Marine Ecosystems. *Science*, 319(February), 948–953.
- 610 Hood, D. A. (2009). Mechanisms of exercise-induced mitochondrial biogenesis in skeletal  
611 muscle. *Applied Physiology, Nutrition and Metabolism*, 34(3), 465–472. doi:  
612 10.1139/H09-045
- 613 Jørgensen, C., Enberg, K., Dunlop, E. S., Arlinghaus, R., Boukal, D. S., Brander, K., ...  
614 Rijnsdorp, A. D. (2007). Ecology: Managing evolving fish stocks. *Science*, 318(5854),  
615 1247–1248. doi: 10.1126/science.1148089

- 616 Koch, R. E., Buchanan, K. L., Casagrande, S., Crino, O., Dowling, D. K., Hill, G. E., ... Stier,  
617 A. (2021). Integrating Mitochondrial Aerobic Metabolism into Ecology and Evolution.  
618 *Trends in Ecology and Evolution*, 1–12. doi: 10.1016/j.tree.2020.12.006
- 619 Le Bourg, B., Bănaru, D., Saraux, C., Nowaczyk, A., Le Luherne, E., Jadaud, A., ... Richard,  
620 P. (2015). Trophic niche overlap of sprat and commercial small pelagic teleosts in the  
621 Gulf of Lions (NW Mediterranean Sea). *Journal of Sea Research*, 103(September), 138–  
622 146. doi: 10.1016/j.seares.2015.06.011
- 623 Lee, S., Lee, Y. M., Kim, K. H., Kim, H. C., Park, C. J., Park, J. W., ... Hwang, H. K. (2018).  
624 Effects of food availability on growth performance and immune-related gene expression  
625 of juvenile olive flounder (*Paralichthys olivaceus*). *Fish and Shellfish Immunology*,  
626 80(May), 348–356. doi: 10.1016/j.fsi.2018.06.021
- 627 McCue, M. D. (2010). Starvation physiology: Reviewing the different strategies animals use  
628 to survive a common challenge. *Comparative Biochemistry and Physiology - A*  
629 *Molecular and Integrative Physiology*, 156(1), 1–18. doi: 10.1016/j.cbpa.2010.01.002
- 630 Mehrabani, S., Bagherniya, M., Askari, G., Read, M. I., & Sahebkar, A. (2020). The effect of  
631 fasting or calorie restriction on mitophagy induction: a literature review. *Journal of*  
632 *Cachexia, Sarcopenia and Muscle*, 11(6), 1447–1458. doi: 10.1002/jcsm.12611
- 633 Metcalfe, N. B., Van Leeuwen, T. E., & Killen, S. S. (2016). Does individual variation in  
634 metabolic phenotype predict fish behaviour and performance? *Journal of Fish Biology*,  
635 88(1), 298–321. doi: 10.1111/jfb.12699
- 636 Monternier, P. A., Teulier, L., Drai, J., Bourguignon, A., Collin-Chavagnac, D., Hervant, F.,  
637 ... Roussel, D. (2017). Mitochondrial oxidative phosphorylation efficiency is  
638 upregulated during fasting in two major oxidative tissues of ducklings. *Comparative*  
639 *Biochemistry and Physiology -Part A : Molecular and Integrative Physiology*, 212(May),  
640 1–8. doi: 10.1016/j.cbpa.2017.06.018
- 641 Morrongiello, J. R., Sweetman, P. C., & Thresher, R. E. (2019). Fishing constrains  
642 phenotypic responses of marine fish to climate variability. *Journal of Animal Ecology*,  
643 88(11), 1645–1656. doi: 10.1111/1365-2656.12999
- 644 Nedergaard, J., & Cannon, B. (2018). Brown adipose tissue as a heat-producing  
645 thermoeffector. In *Handbook of Clinical Neurology* (1st ed., Vol. 156). Elsevier B.V.  
646 doi: 10.1016/B978-0-444-63912-7.00009-6
- 647 Nogueira, V., Walter, L., Avéret, N., Fontaine, E., Rigoulet, M., & Leverve, X. M. (2002).  
648 Thyroid status is a key regulator of both flux and efficiency of oxidative phosphorylation  
649 in rat hepatocytes. *Journal of Bioenergetics and Biomembranes*, 34(1), 55–66. doi:  
650 10.1023/A:1013822820840
- 651 Novak, C. M., Jiang, X., Wang, C., Teske, J. A., Kotz, C. M., & Levine, J. A. (2005). Caloric  
652 restriction and physical activity in zebrafish (*Danio rerio*). *Neuroscience Letters*, 383(1–  
653 2), 99–104. doi: 10.1016/j.neulet.2005.03.048
- 654 Palomera, I., Olivar, M. P., Salat, J., Sabatés, A., Coll, M., García, A., & Morales-Nin, B.  
655 (2007). Small pelagic fish in the NW Mediterranean Sea: An ecological review. *Progress*  
656 *in Oceanography*, 74(2–3), 377–396. doi: 10.1016/j.pocean.2007.04.012
- 657 Queiros, Q., Fromentin, J. M., Gasset, E., Dutto, G., Huiban, C., Metral, L., ... Saraux, C.  
658 (2019). Food in the sea: Size also matters for pelagic fish. *Frontiers in Marine Science*,

- 659 6(JUL), 1–13. doi: 10.3389/fmars.2019.00385
- 660 Rolfe, D. F. S., & Brand, M. D. (1997). The physiological significance of mitochondrial  
661 proton leak in animal cells and tissues. *Bioscience Reports*, 17(1), 9–16. doi:  
662 10.1023/A:1027327015957
- 663 Roussel, D., Salin, K., Dumet, A., Romestaing, C., Rey, B., & Voituron, Y. (2015). Oxidative  
664 phosphorylation efficiency, proton conductance and reactive oxygen species production  
665 of liver mitochondria correlates with body mass in frogs. *Journal of Experimental  
666 Biology*, 218(20), 3222–3228. doi: 10.1242/jeb.126086
- 667 Roussel, D., & Voituron, Y. (2020). Mitochondrial Costs of Being Hot: Effects of Acute  
668 Thermal Change on Liver Bioenergetics in Toads (*Bufo bufo*). *Frontiers in Physiology*,  
669 11(March), 1–10. doi: 10.3389/fphys.2020.00153
- 670 Rumolo, P., Bonanno, A., Barra, M., Fanelli, E., Calabrò, M., Genovese, S., ... Basilone, G.  
671 (2016). Spatial variations in feeding habits and trophic levels of two small pelagic fish  
672 species in the central Mediterranean Sea. *Marine Environmental Research*, 115, 65–77.  
673 doi: 10.1016/j.marenvres.2016.02.004
- 674 Salin, K., Auer, S. K., Anderson, G. J., Selman, C., & Metcalfe, N. B. (2016a). Inadequate  
675 food intake at high temperatures is related to depressed mitochondrial respiratory  
676 capacity. *Journal of Experimental Biology*, 219(9), 1356–1362. doi: 10.1242/jeb.133025
- 677 Salin, K., Auer, S. K., Rey, B., Selman, C., & Metcalfe, N. B. (2015). Variation in the link  
678 between oxygen consumption and ATP production, and its relevance for animal  
679 performance. *Proceedings of the Royal Society B: Biological Sciences*, 282(1812). doi:  
680 10.1098/rspb.2015.1028
- 681 Salin, K., Auer, S. K., Rudolf, A. M., Anderson, G. J., Selman, C., & Metcalfe, N. B. (2016b).  
682 Variation in metabolic rate among individuals is related to tissue-specific differences in  
683 mitochondrial leak respiration. *Physiological and Biochemical Zoology*, 89(6), 511–523.  
684 doi: 10.1086/688769
- 685 Salin, K., Roussel, D., Rey, B., & Voituron, Y. (2012). David and Goliath: A Mitochondrial  
686 Coupling Problem? *Journal of Experimental Zoology Part A: Ecological Genetics and  
687 Physiology*, 317(5), 283–293. doi: 10.1002/jez.1722
- 688 Salin, K., Villasevil, E. M., Anderson, G. J., Auer, S. K., Selman, C., Hartley, R. C., ...  
689 Metcalfe, N. B. (2018). Decreased mitochondrial metabolic requirements in fasting  
690 animals carry an oxidative cost. *Functional Ecology*, 32(9), 2149–2157. doi:  
691 10.1111/1365-2435.13125
- 692 Salin, K., Villasevil, E. M., Anderson, G. J., Lamarre, S. G., Melanson, C. A., McCarthy, I.,  
693 ... Metcalfe, N. B. (2019). Differences in mitochondrial efficiency explain individual  
694 variation in growth performance. *Proceedings of the Royal Society B: Biological  
695 Sciences*, 286(1909). doi: 10.1098/rspb.2019.1466
- 696 Sanderson, S. L., & Cech, J. J. (1992). Energetic Cost of Suspension Feeding versus  
697 Particulate Feeding by Juvenile Sacramento Blackfish. *Transactions of the American  
698 Fisheries Society*, 121(2), 149–157. doi: 10.1577/1548-  
699 8659(1992)121<0149:ecosfv>2.3.co;2
- 700 Saraux, C., Van Beveren, E., Brosset, P., Queiros, Q., Bourdeix, J. H., Dutto, G., ...  
701 Fromentin, J. M. (2019). Small pelagic fish dynamics: A review of mechanisms in the

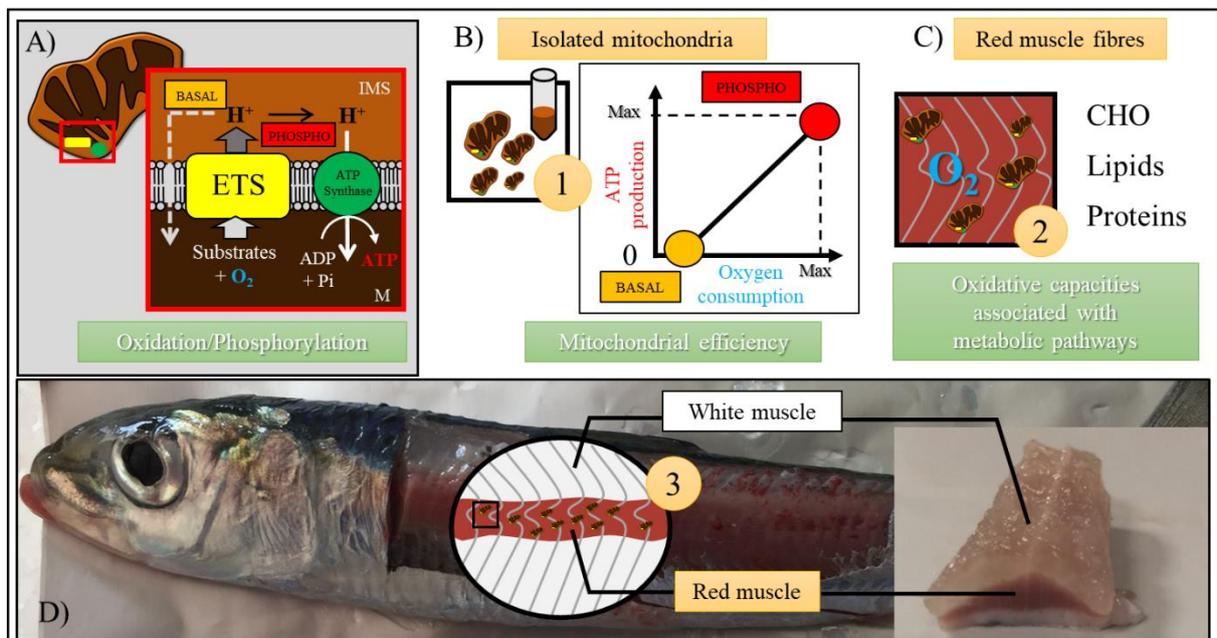
- 702 Gulf of Lions. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 159(xxxx),  
703 52–61. doi: 10.1016/j.dsr2.2018.02.010
- 704 Sibert, J., Hampton, J., Kleiber, P., & Maunder, M. (2006). Biomass, Size, and Trophic Status  
705 of Top Predators in the Pacific Ocean. *Science*, 314(March), 1773–1777. doi:  
706 10.1126/science.1135347
- 707 Sommer, U., Paul, C., & Moustaka-Gouni, M. (2015). Warming and ocean acidification  
708 effects on phytoplankton - From species shifts to size shifts within species in a  
709 mesocosm experiment. *PLoS ONE*, 10(5), 1–17. doi: 10.1371/journal.pone.0125239
- 710 Sun, L., & Chen, H. (2009). Effects of ration and temperature on growth, fecal production,  
711 nitrogenous excretion and energy budget of juvenile cobia (*Rachycentron canadum*).  
712 *Aquaculture*, 292(3–4), 197–206. doi: 10.1016/j.aquaculture.2009.04.041
- 713 Teulier, L., Rouanet, J. L., Letexier, D., Romestaing, C., Belouze, M., Rey, B., ... Roussel, D.  
714 (2010). Cold-acclimation-induced non-shivering thermogenesis in birds is associated  
715 with upregulation of avian UCP but not with innate uncoupling or altered ATP  
716 efficiency. *Journal of Experimental Biology*, 213(14), 2476–2482. doi:  
717 10.1242/jeb.043489
- 718 Teulier, L., Thorat, E., Queiros, Q., McKenzie, D. J., Roussel, D., Dutto, G., ... Saraux, C.  
719 (2019). Muscle bioenergetics of two emblematic Mediterranean fish species: *Sardina*  
720 *pilchardus* and *Sparus aurata*. *Comparative Biochemistry and Physiology -Part A :*  
721 *Molecular and Integrative Physiology*, 235(June), 174–179. doi:  
722 10.1016/j.cbpa.2019.06.008
- 723 Thorat, E., Queiros, Q., Roussel, D., Dutto, G., Gasset, E., McKenzie, D. J., ... Teulier, L.  
724 (2021a). Changes in foraging mode caused by a decline in prey size have major  
725 bioenergetic consequences for a small pelagic fish, Dryad, Dataset,  
726 <https://doi.org/10.5061/dryad.xpvnv0kfp>
- 727 Thorat, E., Roussel, D., Chinopoulos, C., Teulier, L., & Salin, K. (2021b). Low oxygen levels  
728 can help to prevent the detrimental effect of acute warming on mitochondrial efficiency  
729 in fish. *Biology Letters*, 17.
- 730 Toyomizu, M., Kikusato, M., Kawabata, Y., Azad, M. A. K., Inui, E., & Amo, T. (2011).  
731 Meat-type chickens have a higher efficiency of mitochondrial oxidative phosphorylation  
732 than laying-type chickens. *Comparative Biochemistry and Physiology - A Molecular and*  
733 *Integrative Physiology*, 159(1), 75–81. doi: 10.1016/j.cbpa.2011.01.020
- 734 Van Beveren, E., Bonhommeau, S., Fromentin, J. M., Bigot, J. L., Bourdeix, J. H., Brosset,  
735 P., ... Saraux, C. (2014). Rapid changes in growth, condition, size and age of small  
736 pelagic fish in the Mediterranean. *Marine Biology*, 161(8), 1809–1822. doi:  
737 10.1007/s00227-014-2463-1
- 738 Van Der Lingen, C. D. (1995). Respiration rate of adult pilchard *Sardinops sagax* in relation  
739 to temperature, voluntary swimming speed and feeding behaviour. *Marine Ecology*  
740 *Progress Series*, 129(1–3), 41–54. doi: 10.3354/meps129041
- 741 Webb, P. W. (1998). Entrainment by river chub *Nocomis micropogon* and smallmouth bass  
742 *Micropterus dolomieu* on cylinders. *Journal of Experimental Biology*, 201(16), 2403–  
743 2412.
- 744 Zangarelli, A., Chanseau, E., Morio, B., Brugère, C., Mosoni, L., Rousset, P., ... Walrand,

- 745 S. (2006). Synergistic effects of caloric restriction with maintained protein intake on  
746 skeletal muscle performance in 21-month-old rats: a mitochondria-mediated pathway.  
747 *The FASEB Journal*, 20(14), 2439–2450. doi: 10.1096/fj.05-4544com
- 748 Zarubin, M., Farstey, V., Wold, A., Falk-Petersen, S., & Genin, A. (2014). Intraspecific  
749 differences in lipid content of calanoid copepods across fine-scale depth ranges within  
750 the photic layer. *PLoS ONE*, 9(3), 1–10. doi: 10.1371/journal.pone.0092935

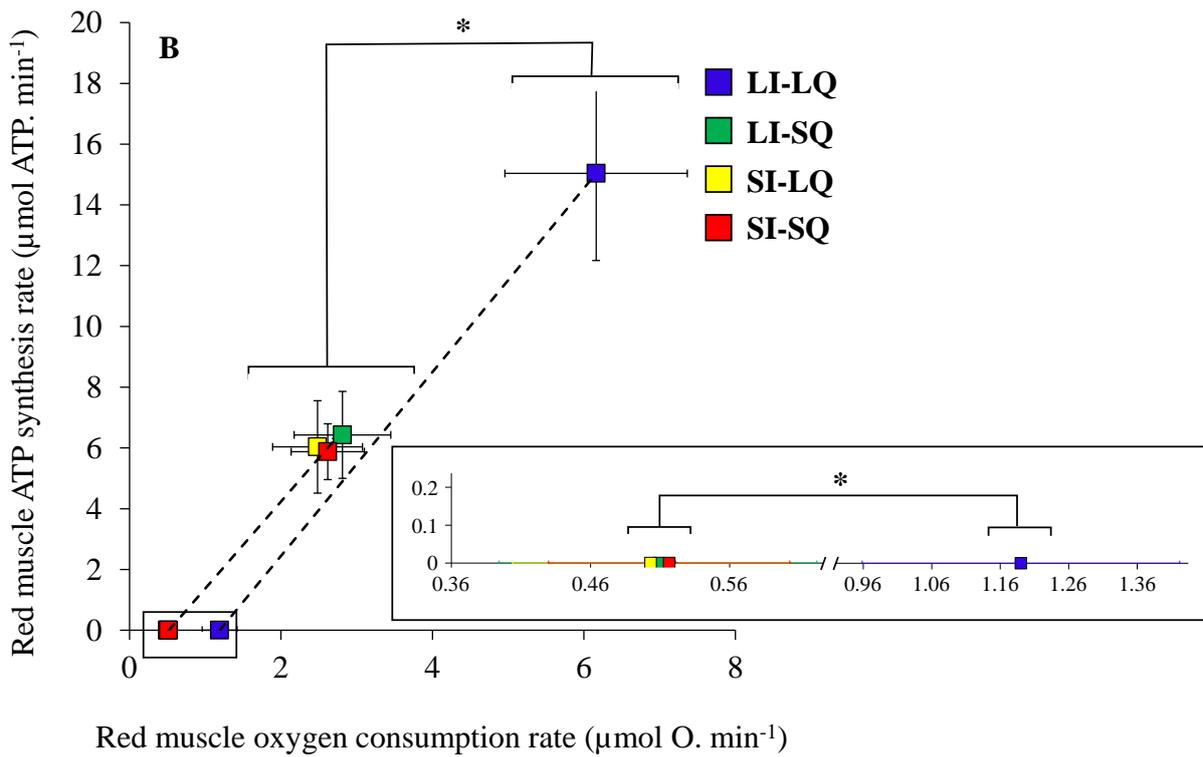
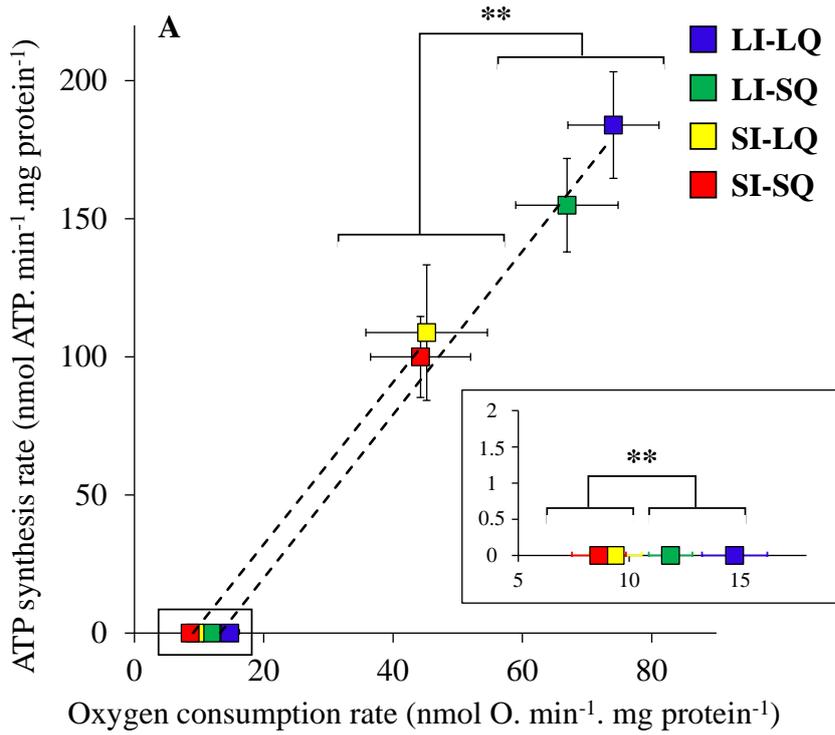
751 **FIGURES**  
752

753 **Figure 1. Illustration of the integrative levels of the red muscle bioenergetics in sardine,**  
754 **from isolated mitochondria, to the whole tissue.**

755 Substrates are oxidized by the complexes of the electron transport system (ETS) and ATP is  
756 produced through a phosphorylation process by the ATP synthase. The ETS and ATP synthase  
757 are enclosed in the inner membrane of the mitochondria (panel A). Mitochondrial respiration  
758 rates associated to either basal non-phosphorylating state (BASAL) and/or phosphorylating  
759 state (PHOSPHO) were assessed at different levels of integration. 1) Mitochondrial oxygen  
760 consumption was coupled to the amount of ATP produced, to obtain the mitochondrial  
761 efficiency which is the slope of the linear regression between oxygen consumption and ATP  
762 production, called P/O ratio (panel B). 2) The muscle fibre respiration rates were induced by  
763 addition of different substrates to discriminate the metabolic pathways fuelling the red muscle  
764 (panel C). 3) The whole red muscle oxidation phosphorylation activity was calculated to  
765 estimate the relative importance of the whole muscle bioenergetics. The red muscle is  
766 positioned along the lateral line and is clearly separated from the white muscle (panel D). ETS:  
767 Electron transport system; ATP: Adenosine triphosphate; ADP: adenosine diphosphate; Pi:  
768 Phosphate inorganic; IMS: intermembrane space of the mitochondrion; M: matrix of the  
769 mitochondrion. See the “Material and Methods” section for further details.



770 **Figure 2. Mitochondrial efficiency of sardine that received different quantities and sizes**  
771 **of food items, at the mitochondrial level** (Panel A; LI-LQ: large food items in large quantities,  
772 n = 11; LI-SQ: large food items in small quantities, n = 12; SI-LQ: small food items in large  
773 quantities, n = 11; SI-SQ: small food items in small quantities, n = 9) **and red muscle level**  
774 (Panel B, LI-LQ: n = 11, LI-SQ: n = 11; SI-LQ: n = 10; SI-SQ: n = 9). In panel A, the two trend  
775 curves drawn are those of the “large food items” (LI:  $y = 3.03x - 44.40$ ) and “small food items  
776 (SI:  $y = 3.19x - 37.96$ ) groups, and in panel B, the trend curves are those of LI-LQ group ( $y =$   
777  $3.17x - 4.52$ ) and of the other groups together ( $y = 2.97x - 1.77$ ). These data were analysed  
778 using a linear-mixed effects model with size and quantity of items as fixed-effects and sex as  
779 random effect. The values shown are means  $\pm$  s.e.m. (the error bars of the basal oxygen  
780 consumption are small enough that they are hidden by the points, see zoom boxes). An asterisk  
781 represents a significantly difference in maximal oxygen consumption, ATP production and  
782 basal oxygen consumption (see zoom boxes) between diets composed of different size food  
783 items (Panel A, difference between LI and SI) and between LI-LQ sardines and other groups  
784 (Panel B; \* $P < 0.05$ ; \*\* $P < 0.01$ ).  
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787 **Figure 3. Basal oxygen consumption at the mitochondrial level as a function of sardine body condition index.** Fish of each treatment are  
788 represented by a coloured circle. Sardines fed with large food items are represented in blue for large quantity (LI-LQ, n = 11) and in green for small  
789 quantity (LI-SQ, n = 12). Yellow and red circles represent sardines fed with small food items, in large (SI-LQ, n = 10) and small (SI-SQ, n = 11)  
790 quantities, respectively. Basal mitochondrial respiration in  $\text{nmol O} \cdot \text{min}^{-1} \cdot \text{mg protein}^{-1}$  is positively correlated to the body condition index when the  
791 BCI is less than 1.07 ( $P < 0.001$ ). Above this threshold, there is no longer a regression between these two parameters.

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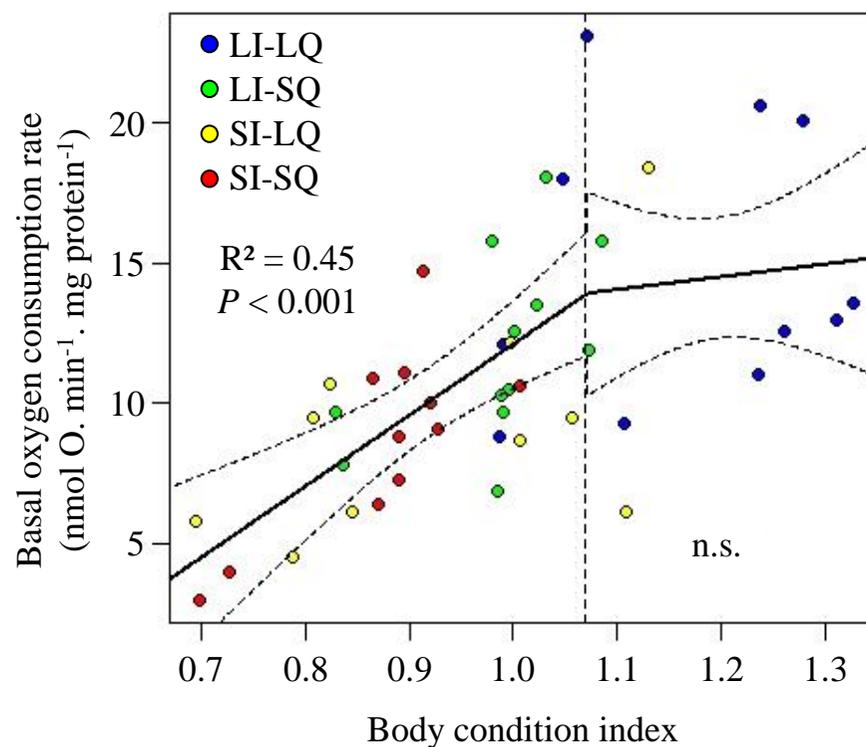
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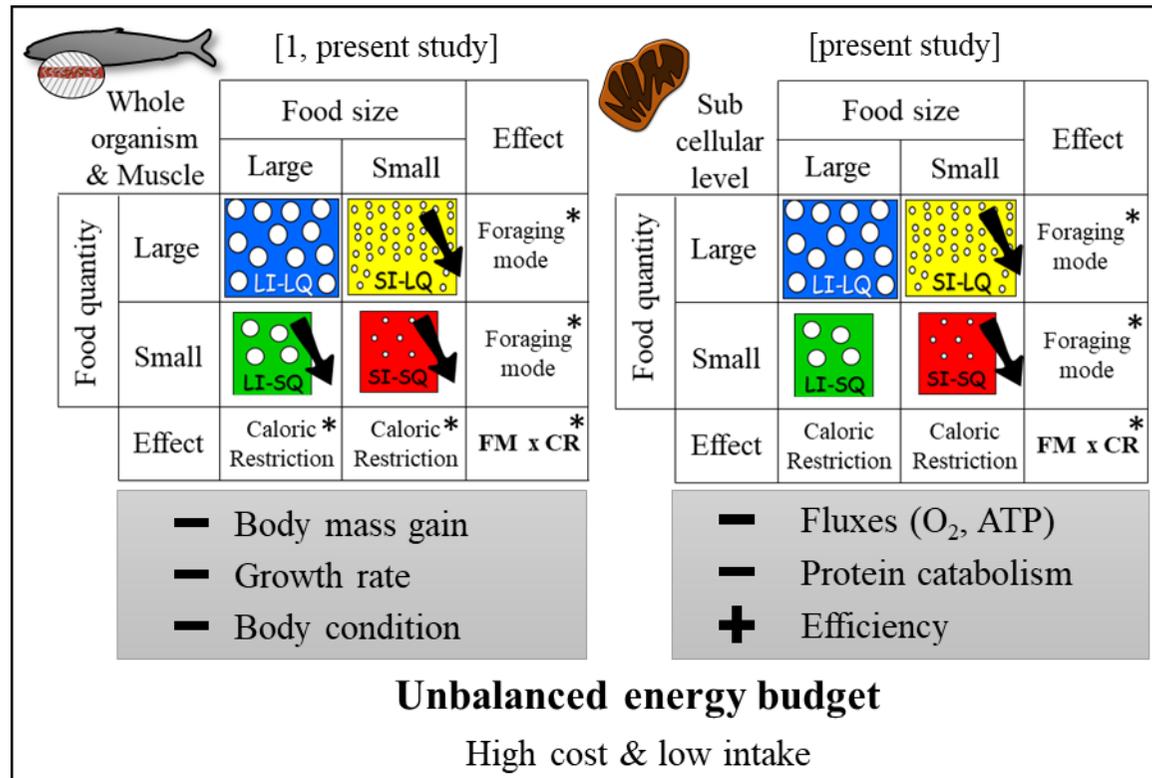
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809 **Figure 4. Whole-organism, muscle, and subcellular consequences of the quantity and/or size of food.** In order to investigate the effect of size  
 810 and/or quantity of food, a fully factorial protocol has been set up. Size and quantity impacted the whole-organism and muscle parameters, whereas  
 811 subcellular bioenergetics have been modified only by size of food items. Significant effects are illustrated by an asterisk. As foraging mode depends  
 812 on food size (Costalago *et al.*, 2015; Garrido *et al.*, 2007), the effect described by size is called “foraging mode” (FM). Lowering the quantity of  
 813 food by 50% induces a severe “caloric restriction” (CR). [1] Queiros *et al.*, 2019



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818 **Table 1. Characteristics of sardines used to measure the respiration of red muscle fibres.** These data correspond to the measurements made  
819 on the day sardines were euthanised. Values are mean  $\pm$  s.e.m. N corresponds to the number of individuals randomly split into 4 treatments, sorted  
820 in three sex categories (male, female and indeterminate). Cumulative growth represents the total length gain in mm, over the entire experiment.  
821 RM/BM ratio corresponds to the relative red muscle mass, which is the proportion of the red muscle mass over the body mass. Data were analysed  
822 with a linear mixed-effect model with size and quantity as fixed-effects and sex as random effect. Data with different superscripts are significantly  
823 different at  $P < 0.05$ . The boxes with the asterisks indicated a global effect of item size (\*\* $P < 0.001$ ).

	LI-LQ	LI-SQ	SI-LQ	SI-SQ	Statistical analysis		
N	8-11	10-12	9-11	10-12			
(M/F/indeterminate)	(6/3/2)	(5/6/1)	(3/5/2)	(3/8/1)			
Final BCI	1.17 ± 0.04 <sup>a</sup>	0.98 ± 0.02 <sup>b</sup>	0.93 ± 0.05 <sup>b</sup>	0.87 ± 0.02 <sup>b</sup>	<b>Size: P &lt; 0.001</b>	824	
					<b>Quantity: P = 0.001</b>	825	
					Size*Quantity: P = 0.061	826	
Fat content (%)	13.46 ± 1.40 <sup>a</sup>	8.86 ± 0.76 <sup>b</sup>	8.12 ± 0.81 <sup>b</sup>	6.93 ± 0.37 <sup>b</sup>	<b>Size: P &lt; 0.001</b>	827	
					<b>Quantity: P = 0.002</b>	828	
					Size*Quantity: P = 0.055	829	
Cumulative growth (mm)	14.29 ± 1.68 <sup>a</sup>	5.05 ± 1.07 <sup>b</sup>	5.27 ± 1.42 <sup>b</sup>	1.64 ± 0.46 <sup>b</sup>	<b>Size: P &lt; 0.001</b>	830	
					<b>Quantity: P &lt; 0.001</b>	831	
					<b>Size*Quantity: P = 0.025</b>	832	
Relative growth (%)	12.55 ± 1.56 <sup>a</sup>	4.35 ± 0.91 <sup>b</sup>	4.60 ± 1.29 <sup>b</sup>	1.34 ± 0.36 <sup>b</sup>	<b>Size: P &lt; 0.001</b>	833	
					<b>Quantity: P &lt; 0.001</b>	834	
					<b>Size*Quantity: P = 0.029</b>	835	
Body mass (g)	19.23 ± 1.38 <sup>a</sup>	13.98 ± 0.62 <sup>b</sup>	14.22 ± 1.19 <sup>b</sup>	12.81 ± 0.73 <sup>b</sup>	<b>Size: P = 0.005</b>	836	
					<b>Quantity: P = 0.001</b>	837	
					Size*Quantity: P = 0.058	838	
Red muscle mass (g)	1.59 ± 0.17 <sup>a</sup>	1.18 ± 0.06 <sup>a,b</sup>	0.98 ± 0.13 <sup>b</sup>	0.91 ± 0.07 <sup>b</sup>	<b>Size: P &lt; 0.001</b>	839	
					<b>Quantity: P = 0.039</b>	840	
RM/BM (%)	8.11 ± 0.39	8.46 ± 0.20	**	6.70 ± 0.45	7.09 ± 0.30	<b>Size: P &lt; 0.001</b>	841

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847 **Table 2. Maximal respiration ETS activity and mitochondrial content of sardine red muscle for each feeding treatment. The maximal**  
848 **respiration rate of ETS induced by FCCP is represented at three different levels of organisation: at the subcellular level (nmol O.min<sup>-1</sup>.mg**  
849 **proteins<sup>-1</sup>) obtained through respiration measurements of isolated mitochondria; at the red muscle fibre level (pmol O<sub>2</sub>.s<sup>-1</sup>.mg muscle<sup>-1</sup>) obtained**  
850 **through respiration measurements of a red muscle sample, and at the red muscle level estimated by multiplying maximal respiration rate at the**  
851 **fibre level by red muscle mass or relative red muscle mass (total: pmol O<sub>2</sub>.s<sup>-1</sup>; specific: pmol O<sub>2</sub>.s<sup>-1</sup>.g fish<sup>-1</sup>). Values are mean ± s.e.m. The**  
852 **mitochondrial content of red muscle is expressed in milligram of mitochondrial proteins per gram of red muscle and was estimated as the ratio**  
853 **between respiration rates at the fibre level and mitochondrial level. Data were analysed with a linear mixed-effects model with size and quantity**  
854 **as fixed-effects and sex as random effect. Different letters indicate a significant difference among groups at P < 0.05. The boxes with the asterisks**  
855 **on the measurements indicates a global effect of item size (\*P < 0.05; \*\*P < 0.01).**  
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	LI-LQ	LI-SQ	SI-LQ	SI-SQ	Statistical analysis
N	9-11	11-12	9-11	9-12	
Maximal respiration ETS activity					
Mitochondrial level (nmol O.min <sup>-1</sup> .mg protein <sup>-1</sup> )	90 ± 9	96 ± 7	59 ± 12	65 ± 12	Size: P = 0.004
Red muscle fibre level (nmol O.min <sup>-1</sup> .mg muscle <sup>-1</sup> )	5 ± 0.8 <sup>a</sup>	3.5 ± 0.4 <sup>a</sup>	3.3 ± 0.4 <sup>a</sup>	5.3 ± 0.9 <sup>a</sup>	Size*Quantity: P = 0.014
Red muscle level	Total (µmol O.min <sup>-1</sup> )				
	6.3 ± 0.9 <sup>a</sup>	4.4 ± 0.7 <sup>a</sup>	3.6 ± 0.7 <sup>a</sup>	4.1 ± 0.8 <sup>a</sup>	n.s.
	Specific (nmol O.min <sup>-1</sup> .g fish <sup>-1</sup> )				
	350 ± 44 <sup>a</sup>	306 ± 38 <sup>a</sup>	245 ± 34 <sup>a</sup>	307 ± 58 <sup>a</sup>	n.s.
Mitochondrial content (mg protein. g muscle <sup>-1</sup> ) <sup>x</sup>	50.9 ± 7.7	34.8 ± 5.4	52.6 ± 8.2	62.2 ± 7.6	Size: P = 0.040

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