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*Original*

Marine heatwaves hamper neuro-immune and oxidative tolerance toward carbamazepine in *Mytilus galloprovincialis* / Nardi, Alessandro; Mezzelani, Marica; Costa, Silvana; D'Errico, Giuseppe; Benedetti, Maura; Gorbi, Stefania; Freitas, Rosa; Regoli, Francesco. - In: ENVIRONMENTAL POLLUTION. - ISSN 1873-6424. - ELETTRONICO. - 300:(2022). [10.1016/j.envpol.2022.118970]

*Availability:*

This version is available at: 11566/295512 since: 2024-04-10T15:55:50Z

*Publisher:*

*Published*

DOI:10.1016/j.envpol.2022.118970

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1 Marine heatwaves hamper neuro-immune and oxidative tolerance toward carbamazepine in *Mytilus*  
2 *galloprovincialis*

3

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18

19 **Keywords:** marine heatwaves; environmental pharmaceuticals; oxidative stress; immune system;  
20 marine mussels; multiple stressors.

21 **Abstract**

22 The increased frequency and intensity of short-term extreme warming phenomena have been  
23 associated to harsh biological and ecosystem outcomes (*i.e.*, mass mortalities in marine organisms).  
24 Marine heatwaves (MHWs), occurring when seasonal temperature threshold is exceeded for at least  
25 5 consecutive days, may reduce the tolerance of coastal species toward additional pressures, but  
26 interactions between such multiple stressors are virtually unexplored. The present study aimed to  
27 characterize in *Mytilus galloprovincialis* the influence of a simulated MHW scenario on the  
28 toxicological effects of the pharmaceutical carbamazepine (CBZ), ubiquitously detected in the marine  
29 environment and chosen as model compound for this relevant class of emerging contaminants. The  
30 bioaccumulation of CBZ and responsiveness of various biological parameters, including immune  
31 system, antioxidant status, lipid metabolism and cellular integrity, were analyzed in exposed mussels  
32 both during and after the end of the heatwave.

33 MHW appeared to strongly modulate accumulation of CBZ, paralleled by weakened  
34 immunocompetence and onset of oxidative disturbance that finally evolved to cellular damages and  
35 lipid metabolism disorders. Elaboration of the overall results through a quantitative Weight of  
36 Evidence model, revealed the highest hazard in organisms exposed to both the stressors 10 days  
37 after the end of the heatwave, suggesting that MHWs could leave a footprint on the capability of  
38 mussels to counteract CBZ toxicity, thus affecting their vulnerability and predisposition to adverse  
39 effects toward multiple stressors.

## 40 Introduction

41 The global ocean warming trend, with a 0.06°C temperature increase per decade since 1900, is a  
42 direct consequence of anthropogenic CO<sub>2</sub> (Garcia-Soto et al., 2021; Bindoff et al., 2013). Ocean  
43 adsorbed almost 90% of excess heat from Earth system since the industrial revolution, reaching an  
44 unprecedented heat content in 2021, the hottest year ever recorded (Cheng et al., 2022). This long-  
45 term and gradual warming is superimposed to an increased frequency of marine heatwaves (MHWs),  
46 short-term extreme events with seawater temperature exceeding a seasonally varying threshold  
47 (usually the 90th percentile) for at least 5 consecutive days (Collins et al., 2019; Frölicher et al., 2019;  
48 Oliver et al., 2019; Hobday et al., 2018; Perkins et al.; 2012).

49 The number of anomalous warm days per year has increased globally by 50% since the early  
50 twentieth century and average intensity of MHWs showed a linear trend of almost +0.1°C per decade  
51 since 1982 (Oliver et al., 2019, 2018). These phenomena, attributed to the anthropic impact on  
52 climate stability, are projected to worsen on a global scale by the end of the century, with many areas  
53 of the ocean experiencing a nearly permanent state of MHW (Collins et al., 2019; Oliver et al., 2019).

54 The Mediterranean Sea represents one of the most endangered areas, where frequency and intensity  
55 of MHWs are predicted to increase, causing severe consequences on marine ecosystems structure,  
56 functioning and services (Ainsworth et al., 2020; Darmaraki et al., 2019; Genevier et al., 2019; Oliver  
57 et al., 2019; Galli et al., 2017). In this respect, MHWs have already been linked to harsh outcomes  
58 and mass mortality events of Mediterranean invertebrates (Strydom et al., 2020; Smale et al., 2019;  
59 Rubio Portillo et al., 2016; Garrabou et al., 2009).

60 The consequence of environmental temperature changes can seriously affect organisms health  
61 condition since temperature is fundamental in shaping aerobic capacity and physiological  
62 homeostasis of marine ectotherms (Sokolova, 2021; Hemraj et al., 2020). Exposure to constantly  
63 elevated temperature caused adverse effects ranging from impairment of molecular and cellular

64 pathways (mitochondria functioning, oxidative stress, signalling), up to energy trade-offs and  
65 alterations of physiological processes, as immune system efficiency, embryonic development,  
66 fertilization and reproduction (Arribas et al., 2022; Crespo et al., 2021; Armstrong et al., 2020; Balogh  
67 and Byrne, 2020; Velez et al., 2017; Bartolini et al., 2013; Byrne et al., 2013; Parker et al., 2009;  
68 Monari et al., 2007; Abele et al., 2002). Biological responsiveness to stress influences the possibility  
69 that organisms resist (maintain performance), recover (restore performance after a decline) or  
70 collapse after thermal stress deriving from marine heatwaves (Leung et al., 2019), and possible  
71 delayed outcomes of such stress have been reported (Minuti et al., 2021; Amorim et al., 2020).

72 In addition to direct effects, MHWs are of interest also for biological consequences of their  
73 interaction with other co-occurring stressors (Arrigo et al., 2020; Przeslawski et al., 2015; Kroeker et  
74 al., 2013), including harmful algal blooms and emerging contaminants (ECs) such as perfluorinated  
75 compounds, microplastics and pharmaceuticals (Carniero et al., 2021, Lim et al., 2021, Reichert et al.,  
76 2021). The widespread occurrence of pharmaceuticals represents a growing risk for coastal areas  
77 (COM/2019/128 final), being a direct consequence of the limited removal by wastewater treatment  
78 plants, inadequate waste handling and accidental discharges, associated to a global increase of drugs  
79 consumption in human medicine and animal husbandry farms (Boxall et al., 2012). Of the 4000  
80 pharmaceuticals released in natural ecosystems, the antiepileptic carbamazepine (CBZ) is one of the  
81 most environmentally relevant, being ubiquitously detected in water column (up to tens of  $\mu\text{g L}^{-1}$ )  
82 and frequently measured in aquatic invertebrates (Mezzelani et al., 2020; Miller et al., 2019; Álvarez-  
83 Muñoz et al., 2018). Among these organisms, previous studies showed that dissolved and particulate-  
84 bound carbamazepine can be accumulated in *Mytilus galloprovincialis* through both gills and  
85 digestive gland, being rapidly uptaken and metabolized (Serra-Compte et al., 2018; Boillot et al.,  
86 2015). Carbamazepine was also reported to affect several physiological and reproductive processes

87 in aquatic non-target species with potential deleterious consequences on wild populations and  
88 ecosystem services (Mezzelani and Regoli, 2022; Mezzelani et al., 2021; Almeida et al., 2018).

89 Despite previous studies revealed that ocean and acidification can modulate the bioavailability and  
90 effects of several classes of contaminants, *e.g.* trace metals and polycyclic aromatic hydrocarbons  
91 (Giuliani et al., 2021; Kibria et al., 2021; Nardi et al., 2021, 2018, 2017; Wu et al., 2020; Moreria et  
92 al., 2016; Sokolova and Lannig, 2008), similar interactions were only recently confirmed for  
93 pharmaceuticals, including carbamazepine (Mezzelani et al., 2021; Costa et al., 2020; Almeida et al.,  
94 2021). In addition, the majority of studies were carried out at constant or linearly increasing  
95 temperature values, while the effects of pulsed thermal stress (MHWs) or the possibility of carry-  
96 over alterations, have been so far poorly investigated.

97 In the present study, Mediterranean mussel *Mytilus galloprovincialis* were exposed to carbamazepine  
98 under a realistic MHW scenario, to test the hypothesis that marine heatwave has detrimental or  
99 delayed outcomes on drug accumulation and effects. *M. galloprovincialis* was selected as test species  
100 due to its ecological, economic and ecotoxicological value (Musella et al., 2020), being recognized as  
101 a suitable bioindicator in the Mediterranean Sea also toward the increasing occurrence of MHWs and  
102 pharmaceuticals, as carbamazepine (Almeida et al., 2021; Mezzelani et al., 2020; Darmaraki et al.,  
103 2019; Galli et al., 2017). Drug bioaccumulation and a wide panel of biochemical, cellular and  
104 histological markers were selected to represent the main pathways of cellular disturbance and stress-  
105 response: the neuroendocrine-immune system, antioxidant defenses, lipid metabolism and oxidative  
106 damages were measured in mussels tissues during, at the end and ten days after the MHW event.

107 The overall results were finally integrated through a quantitative Weight Of Evidence (WOE) model  
108 that elaborates specific hazard indices based on the number, magnitude and toxicological relevance  
109 of observed responses (Regoli et al., 2019). This approach provides quantitative insights on multiple

- 110 stressors, useful to highlight vulnerability of marine species to interactions between commonly found
- 111 pharmaceuticals and the increasing intensity, frequency and duration of marine heatwaves.

## 112 **Materials and Methods**

### 113 *Animal collection and experimental design*

114       Mussels, *Mytilus galloprovincialis* ( $5.3 \pm 0.5$  cm shell length), were obtained in October 2019  
115 from a shellfish farm in an unpolluted area of central Adriatic Sea (Mezzelani et al., 2020). As soon as  
116 their arrival to laboratory facilities, the whole soft tissues of 15 organisms were dissected for the  
117 determination of CBZ levels in wild specimens before the acclimation period. Organisms were  
118 maintained for 7 days in aquaria with aerated artificial seawater (ASW; Instant Ocean®) at local  
119 seasonal environmental conditions of salinity 35, temperature 18 °C and pH 8.20.

120       Mussels were then randomly assigned to eight tanks, each containing 60 organisms in 20 L, and  
121 exposed for 20 days to clean or carbamazepine contaminated ASW either at constant seasonal  
122 environmental temperature or under marine heatwave scenario, according to the four following  
123 treatments, performed in duplicate: CTL, control condition at seasonal climatological sea surface  
124 temperature ( $T_{CSST} = 18^{\circ}\text{C}$ ); CBZ, carbamazepine exposure ( $1 \mu\text{g L}^{-1}$ ) at  $T_{CSST}=18^{\circ}\text{C}$ ; MHW, marine  
125 heatwave scenario (peaking temperature =  $22.5^{\circ}\text{C}$ , further details are given below and in  
126 Supplementary Information Figure SF1); MHW + CBZ, carbamazepine exposure ( $1 \mu\text{g L}^{-1}$ ) under  
127 marine heatwave scenario. The exposure dose of carbamazepine reflects environmental levels in  
128 coastal areas (Mezzelani et al., 2018, 2020; Almeida et al., 2021), while marine heatwave scenario  
129 was reconstructed based on oceanographic data of events occurred in the Adriatic Sea in late  
130 summer – early autumn of 2014 and 2019 ([www.marineheatwaves.org/tracker](http://www.marineheatwaves.org/tracker), coordinates: 43.625,  
131 13.625; cumulative intensity of events:  $26.8^{\circ}\text{C}$  and  $40.4^{\circ}\text{C}$ , respectively; duration: 12 and 15 days,  
132 respectively). Temperature for marine heatwave scenario was increased daily by  $0.9^{\circ}\text{C}$  until the peak  
133 was reached ( $22.5^{\circ}\text{C}$ , day 5 and 6), then it was daily decreased with the same slope until the  
134 climatological mean temperature was restored ( $18^{\circ}\text{C}$ , day 11), and maintained constant for 10  
135 additional days, as “recovery” phase from the marine heatwave. Water was changed every other day,

136 and carbamazepine re-dosed. Organisms in each tank were fed 24h prior the water change with 500  
137  $\mu\text{L}$  of an unpolluted commercial mixture of zooplankton (Brightwell Zooplanktos-S, size range 50-300  
138  $\mu\text{m}$ ) for filter-feeding organisms, according to manufacturer indications.

139 From each experimental condition, 40 organisms (20 per duplicate tank) were randomly sampled  
140 and dissected at three experimental times: T1 (day 6), T2 (day 11) and T3 (day 20) which represented  
141 the peak of heatwave (T1), the end of heatwave (T2), and 10-days post heatwave (T3) respectively.  
142 The choice of 10 days after the end of the heatwave was considered appropriate to highlight  
143 persistence or onset of adverse outcomes after a comparable period of pulsed thermal stress.

144 The whole soft tissues of 15 individuals were used for analyses of CBZ bioaccumulation (5 pools,  
145 each constituted by 3 organisms, stored at  $-20^{\circ}\text{C}$  after dissection) while the haemolymph was  
146 withdrawn (5 pools, each constituted by 3 organisms), partly immediately processed for in vivo  
147 analyses and partly fixed in Carnoy's solution until nuclear alterations analysis. For biomarker  
148 analyses, digestive glands and hemolymph were collected from other 20 individuals (5 pools, each  
149 constituted by tissues of 4 organism, rapidly frozen in liquid nitrogen and maintained at  $-80^{\circ}\text{C}$ ). For  
150 histological analyses, digestive glands of 5 additional organisms were excised, flash frozen separately  
151 and maintained at  $-80^{\circ}\text{C}$ .

152

### 153 *Chemical analyses*

154 Concentrations of CBZ in mussels whole soft tissues (n=5) were determined by High Performance  
155 Liquid Chromatography with fluorometric and diode array detectors. Information on reagents, as well  
156 as detailed extraction and analytical protocols, including QA/QC procedures, are given in  
157 Supplementary Information.

158

### 159 *Biomarkers analyses*

160 Validated protocols were used to analyze the following classes and typologies of biomarkers  
161 (n=5, details are given in Supplementary Information): immunological responses (haemocytes  
162 lysosomal membrane stability, granulocytes vs hyalinocytes ratio and phagocytosis rate), cholinergic  
163 effects (acetylcholinesterase activity in haemolymph); levels of antioxidant defenses (activity of  
164 catalase, Se-dependent glutathione peroxidases, total glutathione peroxidases, glutathione S-  
165 transferases, glutathione reductase, content of total glutathione) and total oxyradical scavenging  
166 capacity (TOSC) toward peroxy radical ROO•, hydroxyl radical HO• and peroxynitrite ONOO-, in the  
167 digestive gland; lipid metabolism (acyl-CoA oxidase activity and neutral lipids content) and  
168 peroxidation (malondialdehyde concentration and lipofuscin content) in the digestive gland; onset  
169 genotoxic damage (DNA fragmentation and micronuclei frequency, in haemocytes).

170

#### 171 *Statistical analyses and weighted elaboration*

172 Data visualization and statistical analyses for CBZ bioaccumulation and biomarkers data were  
173 performed using RStudio (version 1.2.5033). Data were checked for normal distribution (Shapiro-Wilk  
174 test) and homogeneity of variances (Levene's test); when assumptions were not fulfilled, data were  
175 transformed using Box-Cox transformation (power transformation, R package "MASS"). Effect of the  
176 factors "CBZ Exposure" (two levels: 0 and 1  $\mu\text{g L}^{-1}$ ), "Temperature Scenario" (two levels: constant and  
177 marine heatwave), "Experimental Time" (three levels: T1, T2 and T3) and their interactions on CBZ  
178 bioaccumulation and biological parameters were assessed using a generalized linear model (three-  
179 way ANOVA, Table 1); Tukey HSD (HSD) *post-hoc test* was applied for comparing the means of interest  
180 between different treatments at each sampling time and between different sampling times within  
181 the same treatment. Multivariate principal component analysis (PCA) of bioaccumulation and  
182 biomarkers results was applied to visualize the relationships among the different treatments at each  
183 sampling time.

184 The results on bioaccumulation and biomarkers analyses were further elaborated through a  
185 quantitative Weight Of Evidence (WOE) model that provides synthetic hazard indices for each  
186 typology of data (or Line of Evidence, LOE) before their final integration (Regoli et al., 2019).  
187 Independent elaborations for bioaccumulation (LOE-2) and biomarkers (LOE-3) were based on  
188 magnitude of observed variations, statistical significance compared to controls and weights assigned  
189 to toxicological relevance of measured endpoints. After normalization of indices to a common scale,  
190 individual hazard indices were integrated through a classical weight of evidence approach, and level  
191 of risk assigned to 1 of 5 classes, from Absent to Severe. Whole calculations, detailed flow-charts,  
192 rationale for weights, thresholds and expert judgements have been described in detail in  
193 Supplementary Information (Regoli et al., 2019).

194 **Results**

195 *Carbamazepine bioaccumulation*

196 Carbamazepine in tissues of mussels was below the limit of detection of 1.03 ng g<sup>-1</sup> (d.w.) at the  
197 moment of collection (data not shown). Levels of carbamazepine in whole soft tissues of exposed  
198 mussels highlighted significant interactions between CBZ exposure, temperature scenario and  
199 experimental time (Table 1, Fig. 1). Average CBZ values in MHW+CBZ organisms were almost double  
200 at the peak of heatwave (T1) and 10-days post heatwave (T3) compared to those of mussels exposed  
201 to CBZ-alone: at control temperature, the peak of accumulation was reached at T2, then remaining  
202 almost constant at T3.

203

204 *Immunological and cholinergic alterations*

205 Lysosomal membrane stability in haemocytes was affected by CBZ exposure under the MHW scenario  
206 (Table 1, Fig. 2a): the significant reduction of LMS observed at T1 (peak of heatwave), persisted even  
207 at the end of heatwave (T2), and 10-days post heatwave (T3). No differences among time were  
208 reported for any of the treatments. Significant interactions between CBZ, temperature scenario and  
209 exposure time occurred in granulocytes vs. hyalinocytes ratio (Table 1, Fig. 2b): a bell-shaped  
210 variation characterized MHW+CBZ treatment, which showed a significant increase at T2 followed by  
211 a consistent decrease at T3. Similarly, phagocytosis rate (Table 1, Fig. 2c) was significantly reduced in  
212 MHW+CBZ organisms compared to CBZ alone at T1 and T3. Significant differences of AChE activity  
213 were measured in organisms exposed to CBZ alone compared both to control condition (CBZ vs. CTL)  
214 and to MHW+CBZ organisms, with significantly lower activity in these treatments at T1 and T3 (Table  
215 1, Fig. 2d).

216 *Single antioxidant defenses and total oxyradical scavenging capacity*

217 Catalase activity significantly varied along time with a bell-shaped trend (Table 1, Fig. 3a) in organisms  
218 exposed to CBZ and MHW+CBZ. Similar effects were observed for Se-dep. glutathione peroxidases  
219 (Table 1, Fig. 3b), with enhanced activity measured at T2 compared to T1 and T3; in addition, MHW  
220 alone caused a significant induction of Se-dep- GPx activity persisting from the peak up to 10 days  
221 after the end of heatwave. In MHW+CBZ organisms, total glutathione peroxidases activity  
222 significantly declined at T3 compared to T1 (Table 1; Fig. 3c), while glutathione S-transferases showed  
223 a trend of increasing activity reaching a peak of significant induction at T3 in CBZ-exposed organisms,  
224 independently of temperature scenario (Table 1; Fig. 3d). Glutathione reductase was enhanced by  
225 single and combined stressors, particularly evident at T2 (Table 1; Fig. 3e). Total glutathione increased  
226 in all treatments at T1 remaining elevated at T3 in organisms exposed to CBZ, particularly in  
227 MHW+CBZ condition (Table 1; Fig. 3f). Significant effects of carbamazepine and MHW were  
228 highlighted on TOSC ROO•, TOSC HO• and TOSC ONOO- (Table 1, Fig. 4a, b and c respectively). TOSC  
229 ROO• increased at T2 in organisms exposed to CBZ at control temperature, while in marine heatwave  
230 scenarios (MHW and MHW + CBZ) this trend was inverted and exacerbated by the presence of the  
231 drug. An increased capability to counteract HO• was observed in organisms exposed to marine  
232 heatwave (MHW and MHW + CBZ) at T1 and to MHW+CBZ also at T3. Organisms co-exposed to  
233 MHW+CBZ showed significantly lowered capability to counteract peroxynitrite (TOSC ONOO-)  
234 compared to single stressors both at T1 and T2.

235 *Lipid metabolism and peroxidation*

236 CBZ exposure under MHW scenario resulted in a lowered activity of Acyl CoA oxidase compared to  
237 control temperature at T1 (Table 1, Fig. 5a).

238 The content of neutral lipids generally raised in all the treatments with significant interactions  
239 between CBZ exposure, MHW and time (Table 1, Fig. 5b). CBZ showed a prolonged and increasing  
240 effect for the whole duration of exposure under constant temperature scenario (CBZ treatment),  
241 while the effect was not time dependent when CBZ exposure was combined to MHW. Different  
242 effects of MHW and CBZ were highlighted by divergent responses when organisms were exposed to  
243 single or combined stressors: organisms exposed to MHW also exhibited a marked increase of neutral  
244 lipids at the peak of heatwave (T1), followed by a rapid decrement at T2 and T3. CBZ and MHW (Table  
245 1, Fig. 5c) caused slight and irregular changes of malondialdehyde (MDA) at T1 and T2, respectively,  
246 while no variations were observed in co-exposed organisms, which showed MDA content always  
247 comparable to CTL.

248 Lipofuscin content was significantly affected by interactions of CBZ exposure, MHW and experimental  
249 times (Table 1, Fig. 5d). The drug, independently of the temperature scenario, led to increased levels  
250 of lipofuscin at T1 and T2 in CBZ and MHW+CBZ organisms, while values were comparable to CTL at  
251 T3. A biphasic trend was observed also in MHW treated organisms which showed an initial increase  
252 of lipofuscin at T1, followed by the decrement at T2 and T3 with values which, however, remained  
253 higher compared to CTL even after 10 days of recovery.

254 *Genotoxic damage*

255 Exposure to CBZ and heatwave, alone or in combination determined a significant loss of DNA integrity  
256 at T3 (Table 1, Fig. 6a); in addition, a three phases trend was observed in MHW scenario treatments  
257 (MHW and MHW + CBZ): haemocytes experienced DNA damage accumulation at T1, which dropped  
258 at T2 and furtherly increased at T3. CBZ-exposure also led to an enhancement of micronuclei  
259 frequency at T3 (Table 1, Fig. 6b): interestingly, in MHW+CBZ organisms, the highest frequency of  
260 MN was observed at T1 when no effects were caused by single stressors.

261 *Principal components analysis and weighted elaboration*

262 Principal components analysis carried out for each experimental time on the whole dataset of results  
263 (Fig. 7) provided two-dimensional patterns of separation between treatments, always explaining  
264 more than 50% of total variance. At T1 (Fig. 7a), divergence was observed between the two  
265 temperature scenarios, at T2 single and combined stressors were separated (Fig. 7b), while at T3 a  
266 relevant discrimination was further observed for CBZ exposure along Dimension 1 and for MHW along  
267 Dimension 2, producing a split between MHW+CBZ and other treatments (Fig. 7c).

268 Synthetic hazard indices for each experimental treatment and time of exposure were provided by the  
269 weighted elaboration of bioaccumulation (LOE-2) and biomarkers (LOE-3) results (Fig. 8 and details  
270 in Supplementary Information). Bioaccumulation hazard (LOE-2) for CBZ treatment was classified as  
271 "Slight" at T1, "Major" at T2 and "Moderate" at T3, while for MHW+CBZ treatment was classified as  
272 "Moderate" at T2 and "Major" at T1 and T3. The absence of CBZ exposure and bioaccumulation in  
273 MHW treatment resulted in an "Absent" hazard classification for this treatment. The elaboration of  
274 biomarkers (LOE-3) based on the magnitude of variations compared to CTL organisms and the  
275 toxicological relevance of each analyzed parameter produced for CBZ-treated organisms (CBZ and  
276 MHW+CBZ) a "Moderate" hazard classification at T1 and T2 and a "Slight" hazard classification at T3.  
277 In MHW organisms, hazard was classified as "Moderate" at T1 and "Slight" at T2 and T3. The

278 contribution of each investigated parameter to such hazard classifications, is summarized in  
279 Supplementary Information Table ST2. The final weighted integration of LOE-2 and LOE-3, shown in  
280 Figure 8, revealed a level of risk constantly classified as “Moderate” or “Slight” for the carbamazepine  
281 treatment (CBZ) and marine heatwave scenario (MHW), respectively. When carbamazepine was  
282 dosed under marine heatwave scenario (MHW+CBZ), a “Moderate” risk was assigned at the peak and  
283 at the end of heatwave (T1-T2), while it increased to “Major” after 10 days of recovery from the event  
284 (T3).

## 285 Discussion

286 This study provided clear evidence of the capability of marine heatwaves to modulate the susceptibility to  
287 the pharmaceutical CBZ in mussels.

288 Beside the confirmed capability of *M. galloprovincialis* to accumulate this drug, organisms exposed under  
289 MHW scenario exhibited the highest CBZ tissue levels, even after a recovery period from the heatwave: to  
290 our knowledge this is the first study observing delayed effects on pharmaceuticals uptake after the exposure  
291 to a pulsed thermal stress, which characterizes MHWs. Additional evidence on the modulation of the toxicity  
292 of pharmaceuticals in future oceans derives from the onset of immune system alterations caused by  
293 combined rather than single stressors. This was particularly evident on haemocytes lysosomal membranes,  
294 which lost integrity in co-exposed organisms during all phases of the heatwave and recovery period,  
295 consistently with the elevated accumulation of CBZ. We hypothesize an early disturbance triggered by CBZ  
296 (Mezzelani et al., 2021; Franzellitti et al., 2019; Aguirre-Martínez et al., 2013; Martin-Diaz et al., 2009) and  
297 sustained thereon by thermal stress (Marigómez et al., 2017; Parisi et al., 2017), supported by the reduced  
298 capability of lysosomes to recover heat-damaged membranes, as previously observed in *M. galloprovincialis*  
299 exposed to a secondary stressor (*e.g.* cadmium, Múgica et al., 2015). Synergistic effects of CBZ and MHW  
300 were evident also on haemocytes sub-populations and their functional activity. In co-exposed organisms,  
301 granulocytes-hyalinocytes ratio and phagocytosis activity showed a bell-shaped trend of variation over  
302 MHW phases: a counteracting phase, characterized by an increase of these immunological parameters at  
303 the end of the heatwave, was followed by a significant inhibition observed after 10 days of recovery from  
304 the event, confirming that MHWs modulate CBZ toxicity and the immune system of mussels, potentially  
305 increasing their long-term vulnerability to stressors. The mechanisms behind these effects may involve CBZ-  
306 mediated alterations of the neuroendocrine-immune system (Liu et al., 2018): CBZ was shown to increase  
307 ACh synthesis in non-target organisms (Mizuno et al., 2000) and this neurotransmitter has been recently  
308 suggested to suppress bivalves phagocytosis through the alteration of NF- $\kappa$ B and Ca<sup>2+</sup> signaling pathways  
309 (Cao et al., 2021; Du et al., 2020). The differences of AChE activity observed in this study between organisms

310 exposed to CBZ alone or under marine heatwave scenario, support the hypothesis that the impairment of  
311 immune system in co-exposed organisms is, at least partially, caused by a reduced ACh hydrolysis. Such  
312 alterations might have been exacerbated by a reduced functionality of haemocytes due to an increased  
313 oxidative pressure caused by thermal stress of MHW (Benedetti et al., 2022; Rahman et al., 2019), and  
314 confirmed in co-exposed organisms by the appreciable responsiveness of antioxidant defenses in the  
315 digestive gland.

316 Catalase and Se-dependent glutathione peroxidases in CBZ-treated mussels (CBZ and MHW+CBZ) showed a  
317 temporary increase at the end of the heatwave suggesting a delayed demand of hydrogen peroxide  
318 detoxification (Regoli and Giuliani, 2014), possibly reflecting CBZ-metabolism: in non-target species, this  
319 drug is biotransformed through phase I and II pathways, that may thus promote an intracellular formation  
320 of ROS (Mezzelani et al., 2021; Benedetti et al., 2022). The increased activity of the phase II enzymes  
321 glutathione S-transferases observed in the present study, along with variations of glutathione reductase and  
322 levels of total glutathione, support the hypothesis of biotransformation as a source of ROS worsened by  
323 thermal stress and an increased demand of glutathione metabolism to neutralize derived ROS.

324 The responsiveness of individual antioxidants was paralleled by alterations of the total oxyradical scavenging  
325 capacity: in co-exposed organisms the capability to neutralize hydroxyl and peroxy radicals (TOSC HO• and  
326 TOSC ROO•, respectively), showed trends of variations complementary to CAT and Se-dependent GPx and  
327 analogous to TGSH levels. The early increase of defenses against these ROS and the following variations,  
328 confirm non-synchronous responsiveness of single antioxidants and oxidative challenge during exposure.  
329 On the other hand, the initial depletion of capability to neutralize peroxynitrite (TOSC ONOO-) was followed  
330 by its relevant increase after the thermal stress, suggesting that the acute disturbance of this redox pathway  
331 was partly compensated by the mutual interplay with other antioxidant mechanisms (Regoli and Giuliani,  
332 2014). Overall, the persistence of antioxidants alterations after the recovery from the heatwave, further  
333 corroborates the additional impact of MHWs on oxidative effects of CBZ, with potential energetic costs and  
334 metabolic trade-offs to restore redox homeostasis (Sokolova, 2021).

335 In this respect, a disturbance of lipid metabolism was evidenced in co-exposed organisms, which showed a  
336 moderate decrease of Acyl-CoA oxidase and accumulation of neutral lipids (NL). Both carbamazepine and  
337 thermal stress have been previously suggested to have a role on neutral lipids accumulation (Múgica et al.,  
338 2015; Mezzelani et al., 2021; Martin-Diaz et al., 2009; Dimitriadis et al., 2004), but the effects observed in  
339 this study for combined stressors were different from those of single ones. In particular, co-exposed  
340 organisms accumulated NL in the early phases of the heatwave, and these remained constant throughout  
341 the exposure, despite the end of thermal stress; however, after ten days of recovery, levels of NL were lower  
342 compared to those of organisms exposed to CBZ alone, allowing to hypothesize that lipid metabolism is  
343 affected by reciprocal but still unknown interactions between thermal stress and carbamazepine.

344 Lipofuscin content in tertiary lysosomes was increased by all stressors (alone or in combination) highlighting  
345 that the sustained activation of the antioxidant system could not prevent lipid peroxidation processes in the  
346 early phases of stress, and confirming the progression of oxidative imbalance from the activation of  
347 biochemical defenses to cellular disturbance.

348 Oxidative damages were not limited to lipid peroxidation but also involved DNA integrity and micronuclei  
349 formation: exposure to single stressors promoted DNA fragmentation, particularly at the end of recovery  
350 period, with similar outcomes but no synergistic effects in co-exposed organisms. Conversely, a subtle  
351 enhancement of micronuclei frequency was observed in CBZ-treatments (CBZ and MHW+CBZ), with an  
352 earlier and more evident effect in co-exposed organisms, highlighting a hastening of temperature-mediated  
353 effect on CBZ genotoxicity (Nardi et al., 2017; Yao et al., 2013; Salazar et al., 2009).

354 Principal components analysis provided a detailed perspective on the prevalence of different stressors in  
355 each phase of the experiment. At the peak of the heatwave (T1) a major separation occurred between  
356 organisms exposed at control temperature and those under MHW scenario independently of CBZ exposure,  
357 indicating the early onset of disturbance due to the extreme thermal stress; conversely, at the end of the  
358 heatwave (T2), a major disturbance of CBZ was revealed, suggesting that the need to cope thermal stress  
359 was rapidly met but may be disadvantageous in terms of protection toward chemical disturbance. Lastly,

360 after 10 days from the end of the heatwave (T3), a clear separation occurred between single and combined  
361 stressors, supported by the synergic effects in co-exposed organisms.

362 Differences among treatments and experimental phases were summarized by the weighted elaboration of  
363 bioaccumulation and biological responses data through the Weight of Evidence model (SediquaSoft). The  
364 elaboration of bioaccumulation results (LOE-2), based on the levels of CBZ and the magnitude of variation  
365 compared to CTL organisms, revealed a consistently higher hazard in co-exposed organisms (MHW+CBZ).  
366 For this treatment, the overall integration of the wide panel of analyzed biological traits (LOE-3) revealed a  
367 “Moderate” hazard at the heatwave peak, classification supported by the accumulation of lipid peroxidation  
368 products, immune parameters alterations and effects on lipid metabolism and redox homeostasis; this  
369 “Moderate” hazard classification persisted until the end of the heatwave, sustained by the effects on lipid  
370 peroxidation and metabolism, immune parameters and antioxidant pathways; the hazard decreased to  
371 “Slight” after the recovery phase, with still evident effects on certain immune and antioxidant responses.  
372 The final integration of chemical and biological results through a WOE approach, provided a synthetic hazard  
373 index with the worst classification (“Major”) in co-exposed organisms after 10 days of recovery from the  
374 heatwave, thus highlighting long-lasting synergic interaction of stressors and corroborating the hypothesis  
375 of marine heatwave footprint in organisms coping with CBZ.

376

## 377 **Conclusions**

378 This study showed that the occurrence of short-term and pulsed events of temperature extremes may  
379 enhance the accumulation of CBZ in mussels, causing effects that persist even 10 days after the end of the  
380 heatwave. Interactions among stressors synergistically impaired both the neuroendocrine-immune and  
381 oxidative system of organisms, addressing the intensification of extreme events as a key environmental  
382 challenge, which can exacerbate the consequences of the increasing release of pharmaceuticals. Due to the  
383 ecological relevance of this study referred to Mediterranean conditions, where both MHWs and  
384 pharmaceuticals represent emerging challenges, our findings encourage further investigations to better

385 elucidate reciprocal interactions of such multiple stressors, recovery capacity and long-term perspectives  
386 for biodiversity conservation, environmental impact and climate change risk assessment.

387 **Funding**

388 This work has been supported by the projects PHARMASEA (AquaticPollutants Joint Transnational Call 2020),  
389 and BISPECIAL PTDC/CTA-AMB/28425/2017 (POCI-01-0145-FEDER-028425, FEDER, through COMPETE2020  
390 - Programa Operacional Competitividade e Internacionalização, POCI).

391 **Data availability**

392 The data supporting the conclusions of this article are available at the following link:  
393 <https://figshare.com/s/9c28068c95c8d5661f86>.

394 **Acknowledgements**

395 Graphical Abstract was created with BioRender.com.

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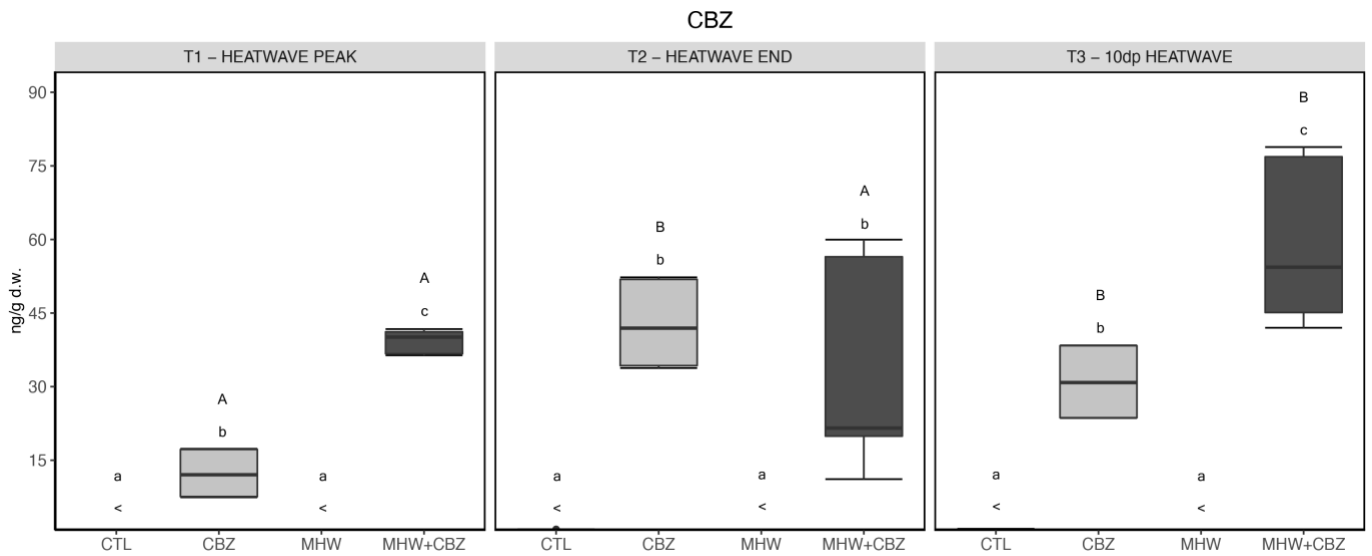
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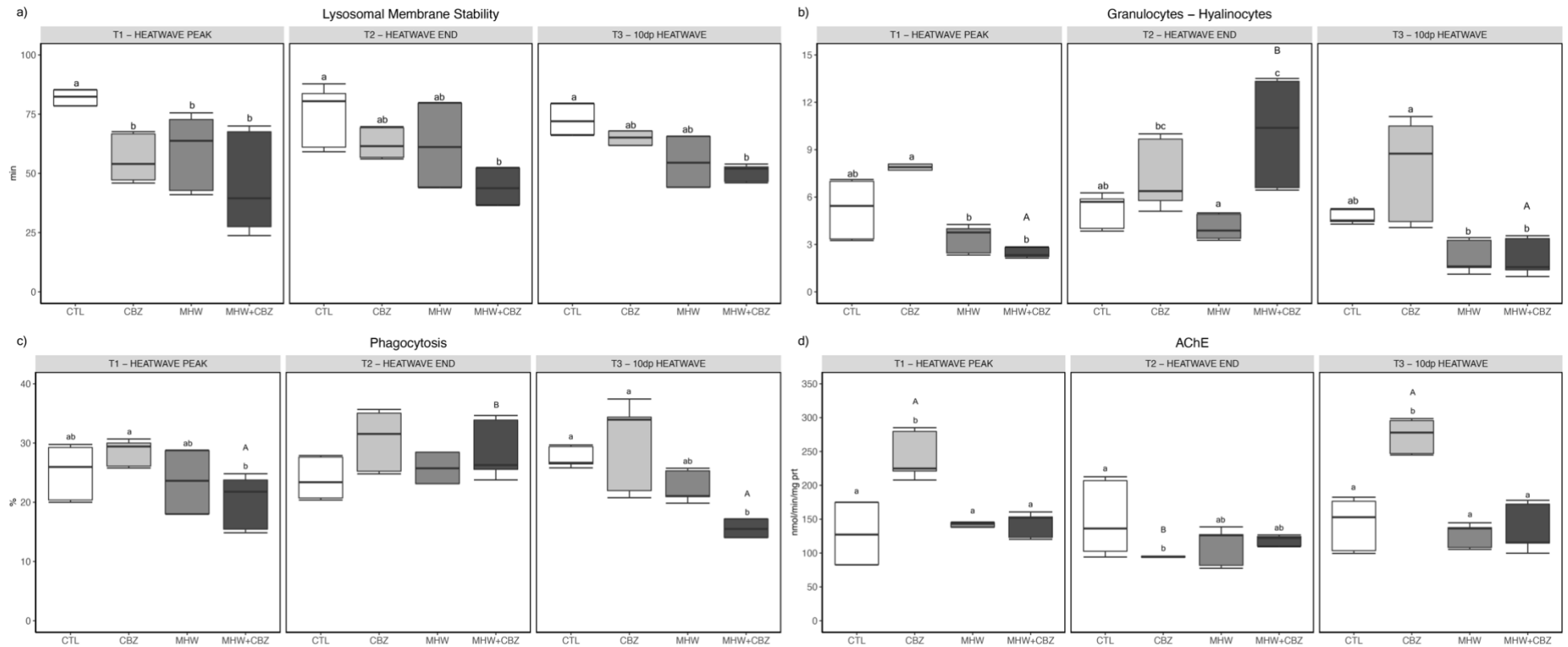
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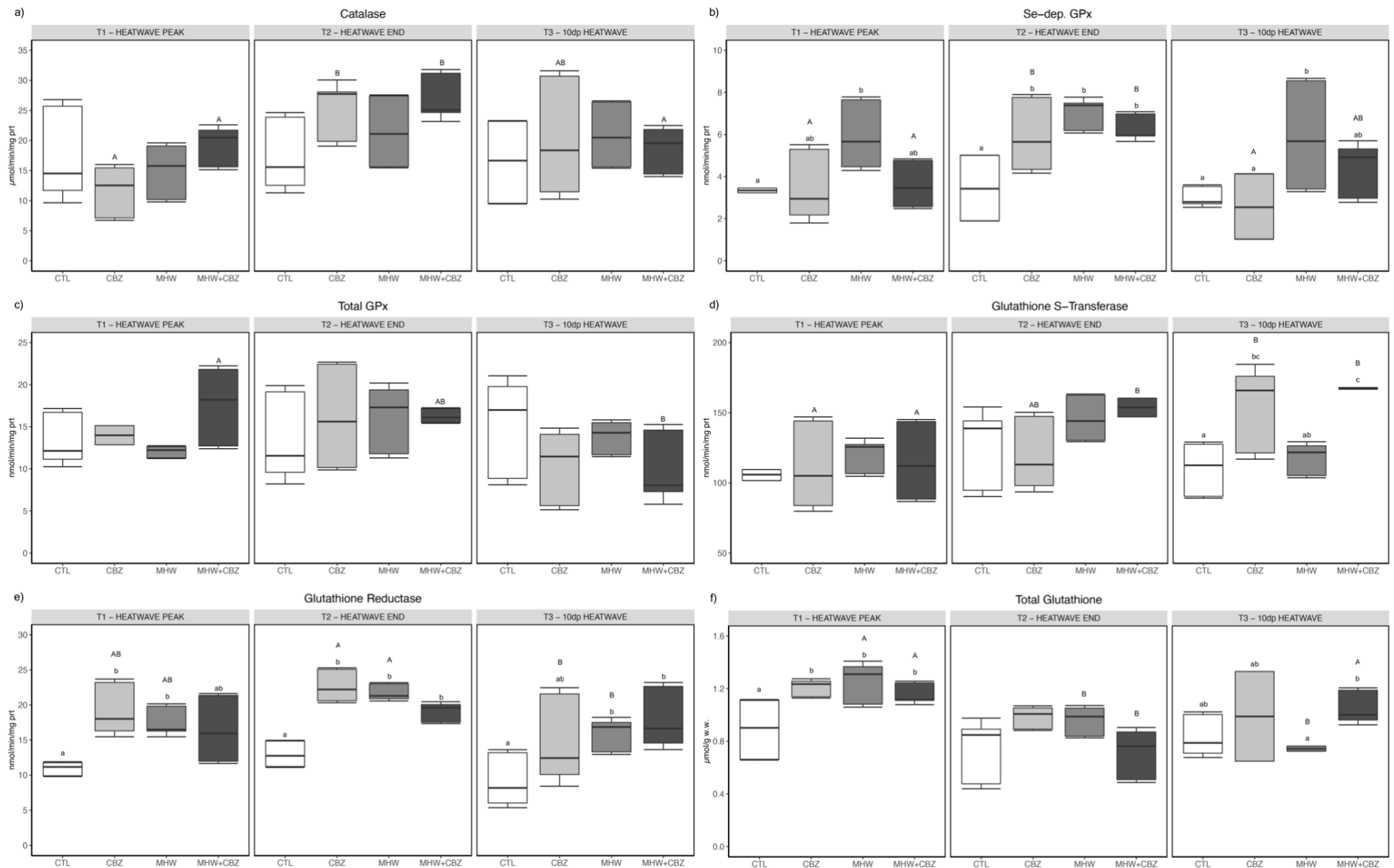
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645 **Figure 1 - Carbamazepine concentration in whole soft tissues of exposed organisms.** Data are given in  $\text{ng g}^{-1}$  dry weight. Lower  
 646 and upper boundaries of each box represent 25th and 75th percentile, respectively, line within the box indicates the median and  
 647 whiskers above and below each box mark highest and lowest values, respectively. CTL (white boxes), control condition: constant  
 648 temperature; CBZ (light grey boxes), CBZ-exposure at constant temperature; MHW (grey boxes), marine heatwave scenario;  
 649 MHW+CBZ (dark grey boxes), CBZ-exposure under marine heatwave scenario. Letters are used to highlight significant differences  
 650 between treatments within the same sampling time (lower case) and among the same treatment along time (upper case). "<"  
 651 indicates concentrations below limit of detection, LOD ( $1.03 \text{ ng g}^{-1} \text{ d.w.}$ ).



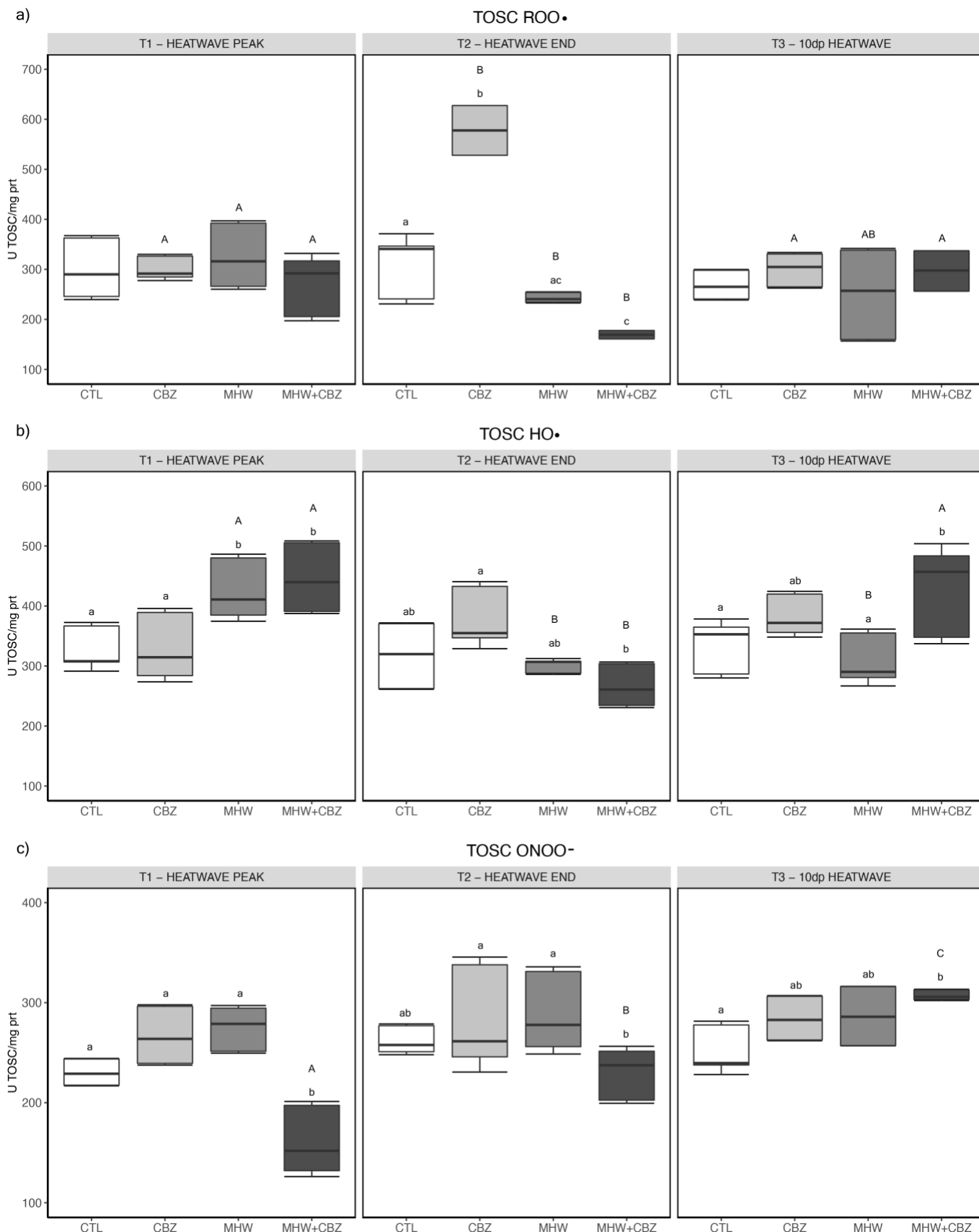
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653 **Figure 2 – Immune and cholinergic alterations.** Lysosomal membrane stability (a), granulocytes/hyalinocytes ratio (b), phagocytosis rate (c), acetylcholinesterase activity (d) in  
 654 haemocytes of exposed mussels. Lower and upper boundaries of each box represent 25th and 75th percentile, respectively, line within the box indicates the median and whiskers  
 655 above and below each box mark highest and lowest values, respectively. CTL (white boxes), control condition: constant temperature; CBZ (light grey boxes), CBZ-exposure at constant  
 656 temperature; MHW (grey boxes), marine heatwave scenario; MHW+CBZ (dark grey boxes), CBZ-exposure under marine heatwave scenario. Letters are used to highlight significant  
 657 differences between treatments within the same sampling time (lower case) and among the same treatment along time (upper case).

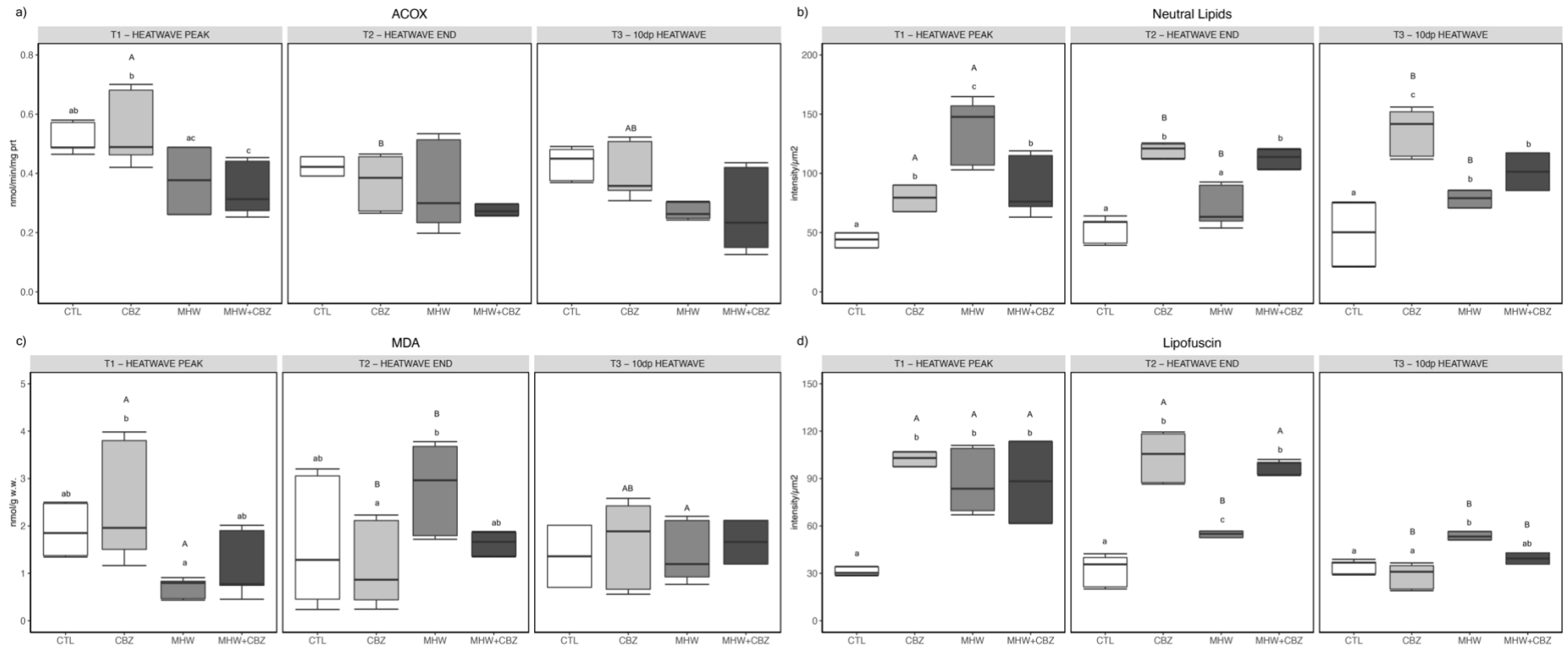


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**Figure 3 – Single antioxidant defenses.** Activity of catalase (a), Se-dependent glutathione peroxidases (b), total glutathione peroxidases (c), glutathione S-transferases (d), glutathione reductase (e) and content of total glutathione (f). Lower and upper boundaries of each box represent 25th and 75th percentile, respectively, line within the box indicates the median and whiskers above and below each box mark highest and lowest values, respectively. CTL (white boxes), control condition: constant temperature; CBZ (light grey boxes), CBZ-exposure at constant temperature; MHW (grey boxes), marine heatwave scenario; MHW+CBZ (dark grey boxes), CBZ-exposure under marine heatwave scenario. Letters are used to highlight significant differences between treatments within the same sampling time (lower case) and among the same treatment along time (upper case).

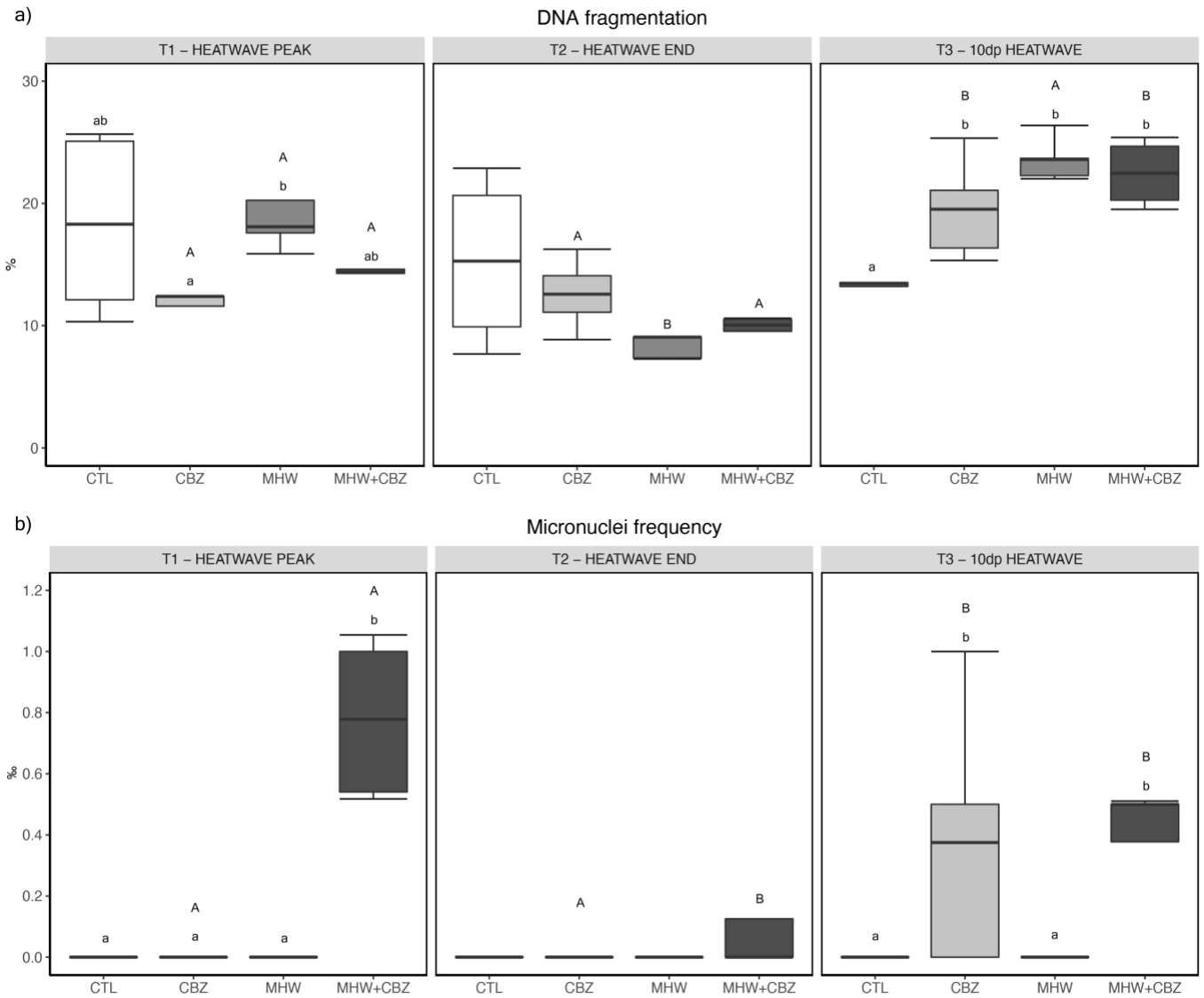


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 665 **Figure 4 - Total oxyradical scavenging capacity.** Overall defenses against peroxy radical (a), hydroxyl radical (b) and peroxynitrite  
 666 (c). Lower and upper boundaries of each box represent 25th and 75th percentile, respectively, line within the box indicates the  
 667 median and whiskers above and below each box mark highest and lowest values, respectively. CTL (white boxes), control  
 668 condition: constant temperature; CBZ (light grey boxes), CBZ-exposure at constant temperature; MHW (grey boxes), marine  
 669 heatwave scenario; MHW+CBZ (dark grey boxes), CBZ-exposure under marine heatwave scenario. Letters are used to highlight  
 670 significant differences between treatments within the same sampling time (lower case) and among the same treatment along  
 671 time (upper case).



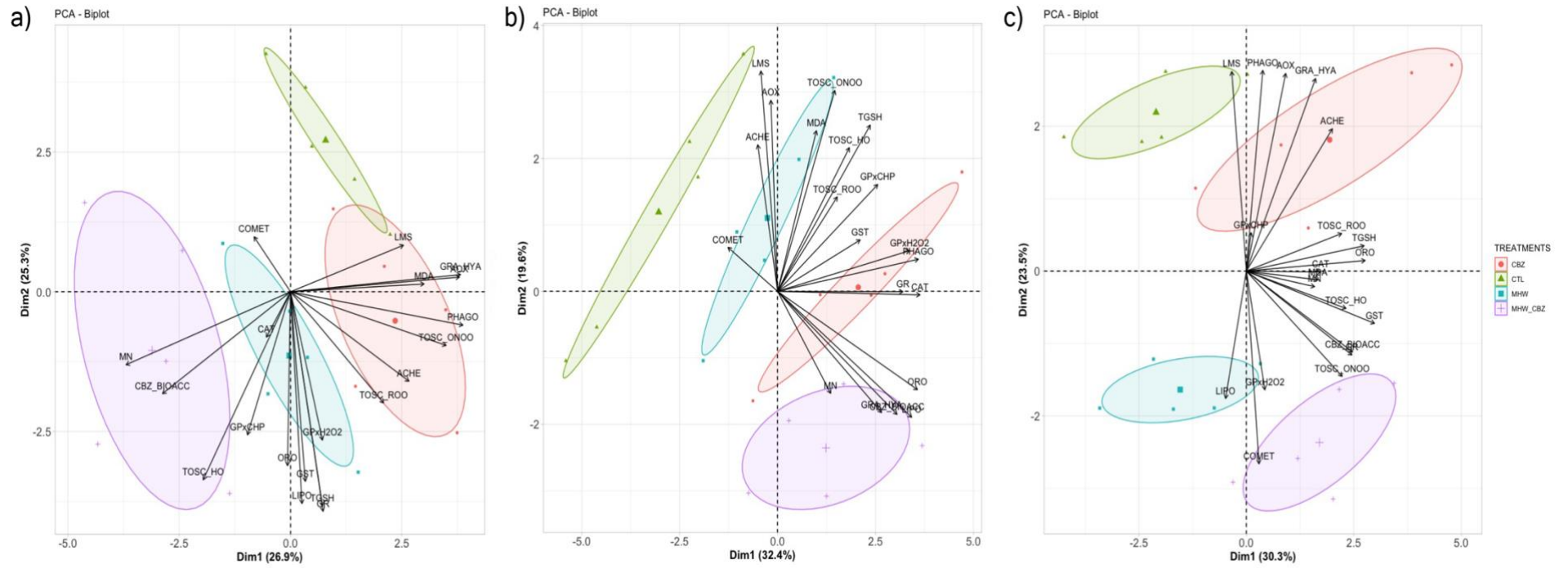
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673 **Figure 5 - Lipid metabolism and peroxidation.** Acyl Co-A oxidase activity (a), neutral lipids content (b), malondialdehyde concentration (c) and lipofuscin content (d). Lower and upper  
 674 boundaries of each box represent 25th and 75th percentile, respectively, line within the box indicates the median and whiskers above and below each box mark highest and lowest  
 675 values, respectively. CTL (white boxes), control condition: constant temperature; CBZ (light grey boxes), CBZ-exposure at constant temperature; MHW (grey boxes), marine heatwave  
 676 scenario; MHW+CBZ (dark grey boxes), CBZ-exposure under marine heatwave scenario. Letters are used to highlight significant differences between treatments within the same  
 677 sampling time (lower case) and among the same treatment along time (upper case).



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679 **Figure 6 - Genotoxic damage.** DNA fragmentation (a) and frequency of micronuclei (b) in haemocytes of exposed mussels. Lower  
 680 and upper boundaries of each box represent 25th and 75th percentile, respectively, line within the box indicates the median and  
 681 whiskers above and below each box mark highest and lowest values, respectively. CTL (white boxes), control condition: constant  
 682 temperature; CBZ (light grey boxes), CBZ-exposure at constant temperature; MHW (grey boxes), marine heatwave scenario;  
 683 MHW+CBZ (dark grey boxes), CBZ-exposure under marine heatwave scenario. Letters are used to highlight significant differences  
 684 between treatments within the same sampling time (lower case) and among the same treatment along time (upper case).






























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Figure 7 - Two-dimensional representation of Principal Components Analysis (PCA) of whole dataset for each experimental checkpoint. T1, day 6, peak of heatwave (a); T2, day 11, end of heatwave (b); T3, day 20, 10-days after heatwave (c).

Treatment	Experimental Checkpoint	LOE-2 (Bioaccumulation)		LOE-3 (Biomarkers)		WOE	
CBZ	T1	SLIGHT		MODERATE		MODERATE	
	T2	MAJOR		MODERATE		MODERATE	
	T3	MODERATE		SLIGHT		MODERATE	
MHW	T1 (peak)	ABSENT		MODERATE		SLIGHT	
	T2 (end)	ABSENT		SLIGHT		SLIGHT	
	T3 (10dp)	ABSENT		SLIGHT		SLIGHT	
MHW+CBZ	T1 (peak)	MAJOR		MODERATE		MODERATE	
	T2 (end)	MODERATE		MODERATE		MODERATE	
	T3 (10dp)	MAJOR		SLIGHT		MAJOR	

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689 **Figure 8 - Weighted elaboration of whole dataset for each treatment in all experimental checkpoints.** Classes of hazard (Absent, white; Slight, light blue; Moderate, yellow; Major, red;

690 Severe, black) are given for each treatment-experimental checkpoint combination for CBZ bioaccumulation (LOE-2), biological effects (LOE-3) and their weighted integration (WOE).

**Table 1** – Three-way ANOVA results for single factors and their interactions; F-values with degrees of freedom and p-values are reported for each tested stressors and interactions for each analyzed parameter. Significant effects are highlighted in bold and italic.

Parameter	CBZ Exposure	Temperature Scenario	Experimental Time	CBZ Exp. x Temp. Scen.	CBZ Exp. x Exp. Time	Temp. Scen. x Exp. Time	CBZ Exp. x Temp. Scen. x Exp. Time
CBZ bioaccumulation	$F_{(1,48)} = 236.1$ $p < 0.001$	$F_{(1,48)} = 10.76$ $p < 0.01$	$F_{(2,48)} = 5.979$ $p < 0.01$	$F_{(1,48)} = 11.05$ $p < 0.01$	$F_{(2,48)} = 5.858$ $p < 0.01$	$F_{(2,48)} = 6.771$ $p < 0.01$	$F_{(2,48)} = 6.933$ $p < 0.01$
Lysosomal membrane stability	$F_{(1,48)} = 19.73$ $p < 0.001$	$F_{(1,48)} = 28.45$ $p < 0.001$	$F_{(2,48)} = 0.001$ $p = 0.999$	$F_{(1,48)} = 0.286$ $p = 0.596$	$F_{(2,48)} = 1.672$ $p = 0.1987$	$F_{(2,48)} = 0.014$ $p = 0.986$	$F_{(2,48)} = 0.724$ $p = 0.490$
Granulocytes - Hyalinocytes ratio	$F_{(1,48)} = 22.48$ $p < 0.001$	$F_{(1,48)} = 25.55$ $p < 0.001$	$F_{(2,48)} = 10.64$ $p < 0.001$	$F_{(1,48)} = 1.114$ $p = 0.296$	$F_{(2,48)} = 4.664$ $p < 0.05$	$F_{(2,48)} = 11.70$ $p < 0.001$	$F_{(2,48)} = 6.602$ $p < 0.01$
Phagocytosis rate	$F_{(1,48)} = 0.480$ $p = 0.492$	$F_{(1,48)} = 18.62$ $p < 0.001$	$F_{(2,48)} = 3.707$ $p < 0.05$	$F_{(1,48)} = 8.163$ $p < 0.01$	$F_{(2,48)} = 3.587$ $p < 0.05$	$F_{(2,48)} = 6.229$ $p < 0.01$	$F_{(2,48)} = 0.542$ $p = 0.585$
AchE activity	$F_{(1,48)} = 18.24$ $p < 0.001$	$F_{(1,48)} = 28.32$ $p < 0.001$	$F_{(2,48)} = 16.12$ $p < 0.001$	$F_{(1,48)} = 12.53$ $p < 0.001$	$F_{(2,48)} = 13.27$ $p < 0.001$	$F_{(2,48)} = 6.033$ $p < 0.01$	$F_{(2,48)} = 14.19$ $p < 0.001$
Catalase activity	$F_{(1,48)} = 1.9024$ $p = 0.174$	$F_{(1,48)} = 2.025$ $p = 0.161$	$F_{(2,48)} = 6.743$ $p < 0.01$	$F_{(1,48)} = 0.057$ $p = 0.812$	$F_{(2,48)} = 2.122$ $p = 0.131$	$F_{(2,48)} = 0.115$ $p = 0.891$	$F_{(2,48)} = 2.584$ $p = 0.086$
Se-dep.glutathione peroxidase activity	$F_{(1,48)} = 1.071$ $p = 0.306$	$F_{(1,48)} = 24.90$ $p < 0.001$	$F_{(2,48)} = 8.486$ $p < 0.001$	$F_{(1,48)} = 9.220$ $p < 0.01$	$F_{(2,48)} = 3.076$ $p = 0.055$	$F_{(2,48)} = 0.566$ $p = 0.572$	$F_{(2,48)} = 0.656$ $p = 0.523$
Total glutathione peroxidase activity	$F_{(1,48)} = 0.005$ $p = 0.943$	$F_{(1,48)} = 0.255$ $p = 0.616$	$F_{(2,48)} = 3.13$ $p = 0.053$	$F_{(1,48)} = 0.379$ $p = 0.541$	$F_{(2,48)} = 4.086$ $p < 0.05$	$F_{(2,48)} = 0.300$ $p = 0.742$	$F_{(2,48)} = 0.928$ $p = 0.402$
Glutathione S-transferases activity	$F_{(1,48)} = 9.044$ $p < 0.01$	$F_{(1,48)} = 7.998$ $p < 0.01$	$F_{(2,48)} = 8.069$ $p < 0.001$	$F_{(1,48)} = 0.063$ $p = 0.803$	$F_{(2,48)} = 7.443$ $p < 0.01$	$F_{(2,48)} = 1.163$ $p = 0.321$	$F_{(2,48)} = 0.37$ $p = 0.693$
Glutathione reductase activity	$F_{(1,48)} = 17.56$ $p < 0.001$	$F_{(1,48)} = 12.27$ $p < 0.01$	$F_{(2,48)} = 9.137$ $p < 0.001$	$F_{(1,48)} = 22.75$ $p < 0.001$	$F_{(2,48)} = 0.036$ $p = 0.964$	$F_{(2,48)} = 0.964$ $p = 0.389$	$F_{(2,48)} = 2.309$ $p = 0.110$
Total glutathione	$F_{(1,48)} = 6.572$ $p < 0.05$	$F_{(1,48)} = 0.740$ $p = 0.394$	$F_{(2,48)} = 14.17$ $p < 0.001$	$F_{(1,48)} = 7.350$ $p < 0.01$	$F_{(2,48)} = 2.090$ $p = 0.135$	$F_{(2,48)} = 1.618$ $p = 0.210$	$F_{(2,48)} = 5.185$ $p < 0.01$
TOSC ROO•	$F_{(1,48)} = 7.529$ $p < 0.01$	$F_{(1,48)} = 39.46$ $p < 0.001$	$F_{(2,48)} = 3.903$ $p < 0.05$	$F_{(1,48)} = 23.94$ $p < 0.001$	$F_{(2,48)} = 7.692$ $p < 0.01$	$F_{(2,48)} = 33.07$ $p < 0.001$	$F_{(2,48)} = 17.27$ $p < 0.001$
TOSC HO•	$F_{(1,48)} = 8.07$ $p < 0.01$	$F_{(1,48)} = 1.789$ $p = 0.187$	$F_{(2,48)} = 9.645$ $p < 0.001$	$F_{(1,48)} = 0.046$ $p = 0.831$	$F_{(2,48)} = 3.342$ $p < 0.05$	$F_{(2,48)} = 15.04$ $p < 0.001$	$F_{(2,48)} = 3.434$ $p < 0.05$
TOSC ONOO-	$F_{(1,48)} = 1.87$ $p = 0.178$	$F_{(1,48)} = 0.488$ $p = 0.488$	$F_{(2,48)} = 14.72$ $p < 0.001$	$F_{(1,48)} = 28.20$ $p < 0.001$	$F_{(2,48)} = 6.288$ $p < 0.01$	$F_{(2,48)} = 5.349$ $p < 0.01$	$F_{(2,48)} = 7.001$ $p < 0.01$
Acyl-CoA oxidase activity	$F_{(1,48)} = 1.056$ $p = 0.309$	$F_{(1,48)} = 28.49$ $p < 0.001$	$F_{(2,48)} = 6.621$ $p < 0.01$	$F_{(1,48)} = 0.159$ $p = 0.692$	$F_{(2,48)} = 0.705$ $p = 0.499$	$F_{(2,48)} = 1.228$ $p = 0.302$	$F_{(2,48)} = 0.255$ $p = 0.776$
Neutral Lipids	$F_{(1,48)} = 56.51$ $p < 0.001$	$F_{(1,48)} = 16.45$ $p < 0.001$	$F_{(2,48)} = 0.266$ $p = 0.768$	$F_{(1,48)} = 39.79$ $p < 0.001$	$F_{(2,48)} = 19.24$ $p < 0.001$	$F_{(2,48)} = 13.24$ $p < 0.001$	$F_{(2,48)} = 3.277$ $p < 0.05$
Malondialdehyde	$F_{(1,48)} = 0.004$ $p = 0.947$	$F_{(1,48)} = 0.397$ $p = 0.532$	$F_{(2,48)} = 0.679$ $p = 0.512$	$F_{(1,48)} = 0.530$ $p = 0.399$	$F_{(2,48)} = 3.521$ $p < 0.05$	$F_{(2,48)} = 7.601$ $p < 0.01$	$F_{(2,48)} = 0.232$ $p = 0.794$
Lipofuscin	$F_{(1,48)} = 82.17$ $p < 0.001$	$F_{(1,48)} = 24.29$ $p < 0.001$	$F_{(2,48)} = 62.96$ $p < 0.001$	$F_{(1,48)} = 35.89$ $p < 0.001$	$F_{(2,48)} = 42.88$ $p < 0.001$	$F_{(2,48)} = 1.480$ $p = 0.238$	$F_{(2,48)} = 9.439$ $p < 0.001$
DNA fragmentation	$F_{(1,48)} = 2.322$ $p = 0.134$	$F_{(1,48)} = 1.576$ $p = 0.215$	$F_{(2,48)} = 21.93$ $p < 0.001$	$F_{(1,48)} = 0.440$ $p = 0.511$	$F_{(2,48)} = 5.786$ $p < 0.01$	$F_{(2,48)} = 10.21$ $p < 0.001$	$F_{(2,48)} = 2.270$ $p = 0.114$
Micronuclei	$F_{(1,48)} = 41.69$ $p < 0.001$	$F_{(1,48)} = 12.48$ $p < 0.001$	$F_{(2,48)} = 6.240$ $p < 0.01$	$F_{(1,48)} = 12.48$ $p < 0.001$	$F_{(2,48)} = 6.240$ $p < 0.01$	$F_{(2,48)} = 7.926$ $p < 0.01$	$F_{(2,48)} = 7.926$ $p < 0.01$