



Title	Enzyme activity modification in adult beetles (<i>Agelastica coerulea</i>) inhabiting birch trees in an ozone-enriched atmosphere
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24 collection, the enzyme activities in the beetles were measured. Elevated O₃ led to a greater
25 total antioxidant activity and lower α - and β -esterase activities, a phenomenon that may
26 suggest an increased resistance of the beetles to stress. Our results are further discussed with
27 regard to biological and toxicological aspects. Collectively, our findings indicate that total
28 antioxidants and α - and β -esterase activities can serve as effective O₃ biomarker systems in
29 this beetle species. This adaptive response of the beetle, which was induced by moderate O₃
30 exposure, should be further tested across generations and for its protection against greater
31 exposure.

32 **Keywords:** adaptive response; antioxidants; beetle; enzymes; esterase; hormesis; insect;
33 ozone

34 **Capsule:** Ozone treatment increased the total antioxidant activity and decreased the α and β
35 esterase activity in a leaf beetle.

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1. Introduction

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46 Tropospheric ozone (O₃) is a naturally occurring gas in the atmosphere. However, O₃ levels
47 have significantly increased throughout the Northern Hemisphere within the last century and
48 remain elevated (Kalabokas et al. 2017; Nagashima et al. 2017; Sicard et al. 2017; Velasco
49 and Retama 2017; Wang et al. 2017; Solomou et al. 2018). The effects of elevated O₃ levels
50 have been widely studied in plants (Agathokleous et al. 2016a; Fuhrer et al. 2016; Jolivet et al.
51 2016; Li et al. 2017); however, limited data exist for insects (Valkama et al. 2007; Lindroth
52 2010). Global change and O₃-induced alterations in plants may alter the suitability of plants
53 to insects, thus affecting plant-insect interactions in a complex manner (Jøndrup et al. 2002;
54 Valkama et al. 2007; Lindroth 2010; Jamieson et al. 2017). In addition, the *disease triangle*
55 conceptual model, which indicates the interactions among the environment, a plant, and a
56 stressor agent, may be disrupted (Chappelka and Grulke 2016).

57 *Agelastica coerulea* (Baly, 1874) (hereafter referred to as the leaf beetle) is a coleopteran
58 species that grazes on Betulaceae plants (Park et al. 2004; Agathokleous et al. 2017a). This
59 beetle has caused severe damage to Japanese white birch (*Betula platyphylla* var. *japonica*)
60 plants of different ages in the Free Air O₃ Controlled Exposure System (FACE) in Sapporo,
61 Japan (Sakikawa et al. 2014, 2016; Vanderstock et al. 2016). This phenomenon was
62 determined to primarily occur in ambient O₃ sites, whereas damage was far less in elevated
63 O₃ sites. In different laboratory experiments where the leaf beetle was not exposed to O₃,
64 overwintered adults were more attracted to leaves treated with elevated O₃ and grazed on
65 them to a greater extent than leaves in ambient O₃. In contrast, 2nd instar larvae showed no
66 differences between the two leaf types (Agathokleous et al. 2017a). In these experiments,
67 total phenolics and condensed tanning were lower in leaves treated with elevated O₃, whereas
68 leaf mass per area was similar between the two O₃ treatments. In further laboratory assays
69 where the leaf beetle was not exposed to O₃, larvae displayed an increased growth rate,

70 consumption index, and efficiency in the conversion of both ingested and digested food when
71 they were fed leaves treated with elevated O₃ (Abu ElEla et al. 2018). This study suggested
72 that larval performance improved when the larvae were fed O₃-treated leaves, thus abrogating
73 the possibility that adults avoided grazing in elevated O₃ sites to ensure leaf palatability for
74 larvae (Agathokleous et al. 2017a). However, whether O₃ treatment affected the
75 biology/physiology of the adult beetles remains unclear.

76 The activities of transaminase enzymes [glutamic-oxaloacetic transaminase (GOT) and
77 glutamic--pyruvic transaminase (GPT)] and carbohydrate hydrolyzing enzymes (trehalase,
78 invertase, and amylase) can be affected by bioinsecticides (Mead 2000). For example,
79 Murdok et al. (1987) studied the midgut enzymes of various coleopteran pests and found that
80 proteinase activity in the midguts and the redox potential varied with pH and that cysteine
81 proteinases were common digestive enzymes. Similarly, plant defense systems against insect
82 herbivores are mediated in part by enzymes that impair the digestive processes of the insect
83 gut.

84 A close relationship has been found between protein synthesis and levels of transaminases in
85 insects (Wigglesworth 2012). These enzymes provide the building blocks for protein
86 synthesis and may be involved in the synthesis of amino acids during metamorphosis (Osman
87 et al., 2015). Hence, GOT and GPT are used as indicators of protein and amino acid
88 metabolism (Upadhyay et al. 2010). Indeed, transaminases are considered key enzymes in the
89 formation of non-essential amino acids, which if formed inside the body are not taken from
90 outside in the metabolism of nitrogen waste gluconeogenesis (Fagan et al. 2002).
91 Phosphatases are enzymes that hydrolyze phosphorous ester or hydride bonds (O'Brien 1967).
92 Alkaline phosphatase (ALP) is involved in the transphosphorylation reaction.

93 Alpha (α) and beta (β) esterases are detoxifying enzymes that hydrolyze ester bonds and
94 widely respond to environmental stimuli (Hemingway and Karunatne 1998). In addition,
95 esterases are involved in the metabolism of organophosphorus, organochlorine, and several
96 classes of endo- and exogenous compounds, thus playing important roles in insecticide
97 resistance. Indeed, several insecticides contain ester bonds that can be hydrolyzed by esterase
98 activity (Sogorb and Vilanova 2002; Zibae et al. 2009; Montella et al. 2012). Changes in
99 esterases may affect insect physiology and behavior because important molecules such as
100 pheromones are hydrolyzed by esterases (Montella et al. 2012).

101 Carbohydrates can be utilized for the production of energy and thus are critical for the
102 development of the insect body. The metabolism of carbohydrates is controlled by trehalase,
103 amylase, and invertase enzymes, which play principal roles in insects during the digestion
104 and utilization of carbohydrates (Wigglesworth 2012).

105 The effects of O₃ on physiological performance of insects and particularly on enzymes such
106 as GOT, GPT, LDH, ALP, α and β esterases, invertase, and trehalase, remain unknown. In
107 this study, we aimed to examine the effects of O₃ on adult leaf beetles, with focus on
108 potential alterations in metabolic enzymes. We also explored relationships among response
109 variables and screened response variables as indices for assessing the effects of O₃ on the
110 beetles (i.e., biomarkers) (Strimbu and Tavel 2010).

111 **2. Materials and Methods**

112 **2.1. Insect samples**

113 Female adult leaf beetles were collected on July 24th, 2016, from Japanese white birch trees
114 grown in the O₃-FACE system of Sapporo Experimental Forest of Hokkaido University,
115 Japan (43°04' N, 141°20' E, 15 m a.s.l.). Three beetles were randomly sampled from each

116 plot for a total of 9 beetles per O₃ treatment. The sampled beetles were 23 days old (i.e. end
117 of their life as overwintered adults), for a total of 63 days from the egg stage. The duration at
118 the other stages was 3, 24, 2, and 12 days for the egg, larval, pre-pupae, and pupal stages,
119 respectively. Beetle sampling was done in two stages. First, dozens of beetles were examined
120 in each plot as to their age. The identification of the beetle age was based upon three aspects:

121 i) mouthparts: beetles develop chewing mouthparts to feed on leaves. A scale of the size
122 of mandibles and their sharpness was created in relation to age. The more they use,
123 the older beetles are, hence, insects of the same age have the same sharpness of
124 the mandibles;

125 ii) body color: all the beetles are dark but the older ones have darker body;

126 iii) body size: the selected samples for analysis should be also of similar size.

127 A pool of 12 beetles, selected following the identification criteria, was created for each plot.
128 Second, 3 beetles were sampled from the pool of each plot for biochemical analyses.

129 This FACE system, which has been in operation since 2014, has six ring units (plots), three
130 of which contain ambient air (AOZ) and three that contain ambient air enriched with O₃
131 (EOZ). The target O₃ concentration in the EOZ was 70 nmol mol⁻¹ during the daytime (>70
132 μmol m⁻²s⁻¹: light compensation point of tested plants; Koike, 1988). O₃ was monitored in
133 each EOZ plot by SM70 Fixed Ozone Monitors (Aeroqual Ltd., Auckland, NZ) and in one
134 AOZ plot using a Model 202 O₃ monitor (2B Technologies, Boulder CO, USA). The mean 10
135 h O₃ concentration was 60 nmol mol⁻¹ in 2014 (August 15 to October 26) and 72 nmol mol⁻¹
136 in 2015 (April 24 to October 26) in the EOZ plots, and 20 nmol mol⁻¹ in 2014 and 34 nmol
137 mol⁻¹ in 2015 in the AOZ plots. In 2016, O₃ treatment started on May 18, and the 10 h mean
138 O₃ concentration (07:00–17:00) in the EOZ plots was 63.5 nmol mol⁻¹ (May 18 to July 24).

139 The monitoring of the ambient O₃ concentration started from June 1. The 10 h ambient O₃
140 concentration was 16.93 nmol mol⁻¹ (May 18 to July 24).

141 Details on the FACE system, O₃ exposure, and meteorological conditions of the previous
142 years have been previously described (Agathokleous et al. 2016b, 2017b).

143 **2.2. Sample analyses**

144 Insects were homogenized for biochemical analysis in a chilled glass Teflon tissue
145 homogenizer (ST-2 Mechanic-Preczyina, Poland). After homogenization, supernatants were
146 kept in a deep freezer at -20°C until use for biochemical assays.

147 The insects were prepared as described by Amin (1998). They were homogenized in distilled
148 water (50 mg mL⁻¹). Homogenates were centrifuged at 8000 rpm for 15 min at 2°C. The
149 deposits were discarded, and the supernatants, referred to as enzyme extracts, were stored for
150 less than one week before analysis.

151 Antioxidants were measured using biodiagnostic kit No. TA 2513. Antioxidants in the sample
152 react with a known quantity of exogenous H₂O₂ of which they eliminate a certain amount.

153 The residual H₂O₂ was determined colorimetrically by an enzymatic reaction which involves
154 the conversion of 3,5-Dichloro-2-benzensulfonate to a colored product read at 505 nm. Total
155 carbohydrates were estimated in acid extract of sample by the phenol-sulfuric acid reaction of
156 DuBois et al. (1956). The absorbance was measured at 490 nm against blank. Total proteins
157 were determined by the method of Bradford (1976), using Coomassie Brilliant blue G-250 for
158 dye. The absorbance was measured at 595 nm against blank prepared from 1 ml of phosphate
159 buffer and 5 ml protein reagent.

160 Alpha- and β-esterases were determined according to Van Asperen (1962), using α-naphthyl
161 acetate or β-naphthyl acetate as substrates. The reaction mixture consisted of 5 ml substrate

162 solution (3×10^{-4} M α - or β -naphthylacetate, 1% acetone, and 0.1 M phosphate buffer, pH 7)
163 and 20 μ l of homogenate. The mixture was incubated for 15 min at 27°C, and 1 ml of diazo
164 blue color reagent was added; the reagent was prepared by mixing 2 parts of 1% diazo blue B
165 and 5 parts of 5% sodium lauryl sulfate. The absorbance was measured at 600 or 555 nm for
166 α - and β -naphthol produced from hydrolysis of the substrate.

167 GOT and GPT were determined colorimetrically according to the method of Reitman and
168 Frankle (1957). The optical density of the produced brown color was measured at 520 nm
169 after 5 minutes, using a spectrophotometer. The method of LDH determination was derived
170 from the formulation recommended by the German Society for Clinical Chemistry (1970).
171 Lactate dehydrogenase catalyzes the conversion of pyruvate to lactate, and NADH is
172 oxidized to NAD during the process. The rate of decrease in NADH is proportional to the
173 LDH activity.

174 Acid and alkaline phosphatases were determined according to the method described by
175 Powell and Smith (1954). In this method, the phenol released by enzymatic hydrolysis of
176 disodium phenylphosphate reacts with 4-aminoantipyrine, and by the addition of potassium
177 ferricyanide, a characteristic brown color is produced. The absorbance was measured at 510
178 nm. The enzyme activity is expressed by unit (U), where 1 unit will hydrolyze 1.0 μ mole of
179 p-nitrophenyl phosphate per minute at 37 °C, and pH 10.4 and 4.8 for alkaline and acid
180 phosphatases, respectively.

181 Digestive enzymes were determined according to the modifications of Amin (1998) to the
182 method described by Ishaaya and Swirski (1976). Generally, 20 μ l of diluted enzyme solution
183 was incubated for 10 min at 30 °C with 250 μ l of 4% sucrose for invertase activity or 3%
184 trehalose solution for trehalase activity, and 230 μ l phosphate buffer (pH 5.4, 0.1 M). The
185 reaction was ceased by adding 250 μ l DNS reagent to each tube in boiling water for 5 min.

186 Samples were cooled, diluted with 2.5 ml H₂O, and the absorbance was measured at 550 nm.
187 Glucose was used as a standard. Appropriate dilutions of enzyme supernatant were used to
188 obtain a linear production of glucose equivalents.

189 Bovine albumin standard was purchased from Stanbio laboratory (Texas, USA). Coomassie
190 brilliant blue G-250 was purchased from Sigma (Sigma Chemical Co.). P-nitroanisole (purity
191 97%) was obtained from Ubichem Ltd. (Hampshire, England) and nicotinamide adenine
192 dinucleotide phosphate (reduced form NADPH) was from BDH Chemicals Ltd. (Poole,
193 England). The rest of the chemicals were of high quality and purchased from commercial
194 local companies. A double beam ultraviolet/visible spectrophotometer (Spectronic 1201,
195 Milton Roy Co., USA) was used to measure the absorbance of colored substances and
196 metabolic compounds.

197 **2.3. Statistical analysis**

198 The cut-off for statistically significant results was set at an α level of 0.05. Because of the *a*
199 *priori* planned comparisons, the data from each response variable were averaged per
200 experimental unit to provide 3 real replicates, and subjected to simple contrasts of Least
201 Squares means (Agathokleous et al. 2016b). The single degree of freedom (k-1) was
202 partitioned to the contrast (a) AOZ vs. EOZ.

203 For statistically significant linear contrasts, the effect magnitude of EOZ was calculated using
204 a bias-corrected Cohen's δ (Hedges and Olkin 1985; Cohen 1988), as described previously
205 (Agathokleous et al. 2016c). The effects were converted into percentile gain, which appeared
206 in the experimental condition using the Cohen's U₃ index (Cohen 1977); δ was converted to
207 the overlapping coefficient (OVL) (Reiser and Faraggi 1999). The effect magnitude was
208 arbitrarily classified as neutral [$\delta = [0.00, 0.50]$], small [$\delta = [0.50, 1.50]$], moderate [$\delta =$
209 [$1.50-3.00$]], or large ($\delta = 3.00+$) (Cohen 1988; Agathokleous et al., 2016b). Absolute δ

210 values in the interval [0.50–1.50] indicated educational significance, whereas δ values >1.50
211 indicated clinical significance (Wolf 1986; Agathokleous et al. 2016b).

212 To explore the relationships between the response variables and to screen the response
213 variables as indices for assessing the effects of O_3 , the data of the response variables were
214 transformed to T -scores, with a mean of 50 and an SD of 10 (Agathokleous et al. 2016d), and
215 subjected to principal component analysis (PCA) with varimax rotation (Kaiser 1958; Abdi
216 and Williams 2010). The null hypothesis of correlations between variables was tested by
217 simple linear regression analysis. Regarding correlations, bivariate correlation (r) values
218 within the arbitrary segments [0.00, 0.10), [0.10, 0.30), [0.30, 0.50), [0.50, 0.70), [0.70, 0.90),
219 and 0.90+ indicated correlations of trivial, low, moderate, large, very large, and nearly perfect
220 magnitude, respectively (Hopkins 2000).

221 The software used for processing and to statistically analyze the data included MS EXCEL
222 2010 (Microsoft ©) and STATISTICA v.10 (StatSoft Inc. ©).

223 **3. Results & Discussion**

224 Insects in the EOZ group had 124% greater total antioxidants than insects in the AOZ group
225 (Fig 1A). In addition, insects in the AOZ group had 184% and 138% greater α and β esterases
226 than insects in the EOZ group (Fig 2). EOZ had a moderate effect on total antioxidants ($\delta =$
227 1.80, $U_3 = 0.96$, OVL = 0.37), α esterases ($\delta = -2.71$, $U_3 = 1.00$, OVL = 0.17), and β
228 esterases ($\delta = -2.16$, $U_3 = 0.98$, OVL = 0.28), which was of both practical and clinical
229 significance. Increased antioxidants may contribute to improving the performance of insects
230 under stress by decreasing damage to lipids and proteins induced by free radicals (Tapia et al.
231 2006; López-Martínez et al. 2012, 2016). The EOZ-induced decrease in esterases may be
232 interpreted as an inhibitory effect of O_3 on the synthesis of α and β esterases (Kurappasamy et
233 al. 2001). However, this may not be the case. Insects can achieve resistance through the

234 modification of enzyme structures to increase the capacity to metabolize harmful products. In
235 this case, the decreased α and β esterase activity due to the EOZ treatment may indicate
236 increased resistance (Wool and Greenberg 1990), along with an enhanced capacity to
237 hydrolyze harmful substances. This, along with a lower hydrolysis of substrates that drive the
238 activity of esterases, is in accordance with the “mutant ali-esterase” theory (Oppenoorth and
239 van Asperen 1960). Hence, esterase activity may serve as a biomarker of resistance to stress,
240 where lower esterase activity is associated with greater resistance (Wool and Greenberg
241 1990).

242 Insects may experience stress indirectly by consuming harmful materials in O₃-affected
243 leaves or directly by breathing O₃ included in the air taken from the tracheae (a tubes
244 network). This study aimed at investigative O₃ effects on the beetle as a sum of direct and
245 indirect effects; insects would experience both direct and indirect effects in an O₃-polluted
246 environment. Hence, this study does not provide the opportunity to separate the direct and
247 indirect effects of O₃ (Telesnicki 2015, 2018). However, previous bioassays, where this
248 beetle was not directly exposed to O₃, suggest that EOZ leaves not only were not harmful but
249 were often preferred over AOZ leaves by the beetles. In addition, the beetles fed with EOZ
250 leaves often had improved nutritional performance compared with beetles fed with AOZ
251 leaves (Agathokleous et al. 2017a; Abu ElEla et al. 2018). Hence, the present study may
252 suggest for the first time a direct biological effect of elevated O₃ on this beetle. The Japanese
253 environmental quality standard for O₃ hourly values is set at 0.06 ppm (Ministry of the
254 Environment, Government of Japan; <https://www.env.go.jp/en/air/aq/aq.html>), which is
255 similar to the O₃ concentration in the EOZ. Based on Japanese and other worldwide (e.g., U.S.
256 EPA) standards, which are set according to the literature using several animal models,
257 adverse EOZ-induced effects on beetles would not be expected to occur at O₃ exposures
258 lower than the standards. Rather, increased oxidative stress below the toxicological threshold

259 may promote health in animal models (Ristow and Schmeisser 2011). In fact, it is known that
260 O₃ can induce the up-regulation of antioxidants in animal models, including humans, which
261 are of an adaptive nature, resulting in potential effects that are beneficial to health (Bocci
262 2006, 2007, 2012). These effects may also protect against a subsequent more massive
263 environmental threat, a phenomenon called *environmental conditioning* (Calabrese et al.
264 2016a,b; Agathokleous 2018). Adaptive responses should be further tested over time and
265 across generations due to potential transgenerational hormetic mechanisms (Calabrese and
266 Mattson 2017; Agathokleous 2018; Agathokleous et al. 2018).

267 Insects in the AOZ and EOZ group did not significantly differ in terms of total carbohydrates
268 (Fig 1B), total proteins (Fig 1C), GOT (Fig 3A), GPT (Fig 3B), LDH (Fig 3C), ALP (Fig 4A),
269 invertase (Fig 4B), and trehalase (Fig 4C). In several response variables, there were large
270 proportional differences between the AOZ and EOZ groups; however, they displayed a large
271 relative standard deviation (RSD). For example, ALP was 1.87 times greater in insects in the
272 EOZ group than in the AOZ group; however, the RSD in the EOZ group was 56.9% vs. 9.8%
273 in the AOZ group.

274 The relationships among response variables were also examined. With regards to PCA, the
275 first three factors, F1, F2, and F3, explained 36.35%, 28.97%, and 24.74% of the total
276 variance, respectively, for a total of 90% (Fig 5). The three response variables with a
277 significant EOZ effect, i.e., the total antioxidants and α and β esterases, had a high loading on
278 the major axis PC1 and explained 47.9% of the variance in this component (Table 1). Total
279 antioxidants were negatively correlated with α and β esterases (Fig 5), suggesting that an
280 increase in total antioxidants is accompanied by a decrease in α and β esterases. Furthermore,
281 the high loading of total antioxidants, and α and β esterases on PC1, reflected a high
282 correlation of these response variables with PC1, suggesting that, along with total
283 antioxidants, α and β esterases may be considered as an interesting biomarker of the effects of

284 O₃ on these insects when the effects are not confounded by other environmental stresses such
285 as drought.

286 Total antioxidants displayed an anticorrelation of a very large magnitude with α and β
287 esterases, and a positive correlation of very large magnitude with LDH (Table 2). This may
288 indicate that esterase reduction is associated with LDH enhancement along with increased
289 glycolytic capacity. It is important that LDH in animal models display a biphasic dose
290 response to stress (Diamantino et al. 2001), i.e., hormesis, which suggests the stimulation of
291 LDH at low exposure levels and the inhibition of LDH at high levels of exposure
292 (Agathokleous 2018). Total antioxidants were negatively correlated with total carbohydrates;
293 however, the *P*-value was not significant (*P* = 0.060). Total carbohydrates displayed a
294 positive correlation of very large magnitude with total proteins and β esterases. ALP was
295 negatively correlated with invertase. All other correlations were not significant.

296 **4. Conclusions**

- 297 • EOZ increased the total antioxidant activity and decreased the α and β esterase
298 activity.
- 299 • The results of this study indicate EOZ-induced oxidative stress in this beetle.
- 300 • Higher antioxidant capacity and lower esterase capacity suggest increased resistance
301 along with a health-promoting capability through the prevention of the accumulation
302 of harmful substances produced during stress, such as reactive oxygen species.
- 303 • Total antioxidants and esterases (α and β) can be utilized as an effective O₃ biomarker
304 system in this beetle.
- 305 • O₃-induced biological responses of the beetle require further experimentations over
306 time and across generations.

- 307 • A further challenging task would be to test whether potential adaptive responses of
308 the beetle to sub-lethal O₃-induced stress result in less harm following larger stress.

309

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319

320 **References**

321 Abdi H, Williams LJ (2010) Principal component analysis. WIREs Computational Statistics
322 2:433–459

323 Abu ElEla S, Agathokleous E, Koike T (2018) Growth and nutrition of *Agelastica coerulea*
324 (Coleoptera: Chrysomelidae) larvae changed when fed with leaves obtained from an O₃-
325 enriched atmosphere. Environ. Sci Pollut Res. doi: 10.1007/s11356-018-1683-1

326 Agathokleous E (2018) Environmental hormesis, a fundamental non-monotonic biological
327 phenomenon with implications in ecotoxicology and environmental safety. Ecotox Environ
328 Safe 148:1042–1053

329 Agathokleous E, Saitanis CJ, Wang X, Watanabe M, Koike T (2016a) A review study on past
330 40 years of research on effects of tropospheric O₃ on belowground structure, functioning, and

331 processes of trees: a linkage with potential ecological implications. *Wat Air Soil Pollut*
332 227:33

333 Agathokleous E, Paoletti E, Saitanis CJ, Manning W, Shi C, Koike T (2016b) High doses of
334 ethylene diurea (EDU) are not toxic to willow and act as nitrogen fertilizer. *Sci Total Environ*
335 566-567:841–850

336 Agathokleous E, Saitanis CJ, Stamatelopoulos D, Mouzaki-Paxinou A-C, Paoletti E,
337 Manning WJ (2016c) Olive oil for dressing plant leaves so as to avoid O₃ injury. *Wat Air Soil*
338 *Pollut* 227:282

339 Agathokleous E, Watanabe M, Eguchi N, Nakaji T, Satoh F, Koike T (2016d) Root
340 production of *Fagus crenata* Blume saplings grown in two soils and exposed to elevated CO₂
341 concentration: an 11-year free-air-CO₂ enrichment (FACE) experiment in northern Japan.
342 *Wat Air Soil Pollut* 227:187

343 Agathokleous E., Sakikawa T, Abu ElEla, SA, Mochizuki T, Nakamura M, Watanabe M,
344 Kawamura K, Koike T (2017a) Ozone alters the feeding behavior of the leaf beetle
345 *Agelastica coerulea* (Coleoptera: Chrysomelidae) into leaves of Japanese white birch (*Betula*
346 *platyphylla* var. *japonica*). *Environ Sci Poll Res* 24:17577–17583

347 Agathokleous E, Vanderstock A, Kita K, Koike T (2017b) Stem and crown growth of
348 Japanese larch and its hybrid F₁ grown in two soils and exposed to two free-air O₃ regimes.
349 *Environ Sci Poll Res* 24:6634–6647

350 Agathokleous E, Kitao M, Calabrese EJ (2018) Environmental hormesis and its fundamental
351 biological basis: Rewriting the history of toxicology. *Environ Res* 165:274–278

352 Amin TR (1998) Biochemical and physiological studies of some insect growth regulators on
353 the cotton leafworm, *Spodoptera littoralis* (Boisd.). Ph.D. thesis, Faculty of Science, Cairo
354 Univ., Egypt

355 Blande JD, Holopainen JK, Niinements Ü (2014) Plant volatiles in polluted atmospheres:
356 stress responses and signal degradation. *Plant Cell Environ* 37:1892–1904

357 Bocci V (2006) Is it true that ozone is always toxic? The end of a dogma. *Toxicol Appl*
358 *Pharm* 216:493–504

359 Bocci VA (2007) Tropospheric ozone toxicity vs. usefulness of ozone therapy. *Arch Med Res*
360 38:265–267

361 Bocci V (2012) How a calculated oxidative stress can yield multiple therapeutic effects. *Free*
362 *Rad Res* 46:1068–1075

363 Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram
364 quantities of proteins utilizing the principle of protein-dye binding. *Anal Biochem* 72:248–
365 254

366 Calabrese EJ (2016a) Preconditioning is hormesis part II: How the conditioning dose
367 mediates protection: Dose optimization within temporal and mechanistic frameworks. *Pharm*
368 *Res* 110:265–275

369 Calabrese EJ (2016b) Preconditioning is hormesis part I: Documentation, dose-response
370 features and mechanistic foundations. *Pharm Res* 110:242–264

371 Calabrese EJ, Mattson MP (2017) How does hormesis impact biology, toxicology, and
372 medicine? *Aging Mech Dis* 3:13

373 Chappelka AH, Grulke NE (2016) Disruption of the ‘disease triangle’ by chemical and
374 physical environmental change. *Plant Biol* 18:5–12

375 Cohen J (1977) *Statistical power analysis for behavioral sciences* (revised edn). New York:
376 Academic Press

377 Cohen J (1988) *Statistical power analysis for the behavioral sciences*, 2nd edn. Lawrence
378 Erlbaum Associates, New Jersey, p 590

379 Diamantino TC, Amadeu E, Soaresa MV, Guilhe CL (2001) Lactate dehydrogenase activity
380 as an effect criterion in toxicity tests with *Daphnia magna*, Straus. *Chemosphere* 45:553–560

381 DuBois M, Gilles KA, Hamilton JK, Rebers PA, Smith F (1956) Colorimetric method for
382 determination of sugars and related substances. *Anal Chem.* 8:350–356

383 Fagan WF, Siemann E, Mitter C, Denno RF, Huberty AF, Woods HA, Elser JJ (2002)
384 Nitrogen in insects: implications for trophic complexity and species diversification, *The Am*
385 *Natural* 160:784–802

386 Fuhrer J, Val Martin M, Mills G, Heald CL, Harmens H, Hayes F, Sharps K, Bender J,
387 Ashmore MR (2016) Current and future ozone risks to global terrestrial biodiversity and
388 ecosystem processes. *Ecol Evol* 6:8785–8799

389 German Society for Clinical Chemistry (1970). Empfehlungen der Deutschen Gesellschaft
390 für Klinische Chemie (DGCK). *Z Klin Chem u Klin Biochem* 8:658–660

391 Hedges LV, Olkin I (1985) *Statistical methods for meta-analysis*, 1st edn. Academic Press,
392 Orlando, FL. 369pp

393 Hemingway J, Karunaratne SHPP (1998) Mosquito carboxylesterases: A review of the
394 molecular biology and biochemistry of a major insecticide resistance mechanism. *Med Vet*
395 *Entomol* 12:1–12

396 Hopkins WG (2000) *A new view of statistics*, <http://newstats.org>. Accessed 29 September
397 2016

398 Ishaaya I, Swirski E (1976) Trehalase, invertase and amylase activities in the black scale,
399 *Saissetia oleae*, and their relation to host adaptability. *J Ins Physiol* 16:1025–1029

400 Jamieson MA, Burkle LA, Manson JS, Runyon JB, Trowbridge AM, Zientek J (2017) Global
401 change effects on plant–insect interactions: the role of phytochemistry. *Curr Opin Ins Sci*
402 23:70–80.

403 Jolivet Y, Bagard M, Cabané M, Vaultier M-N, Gandin A, Afif D, Dizengremel P, Le Thiec
404 D (2016) Deciphering the ozone-induced changes in cellular processes: a prerequisite for
405 ozone risk assessment at the tree and forest levels. *Ann For Sci* 73:923–943.

406 Jøndrup PM, Barnes JD, Port GR (2002) The effect of ozone fumigation and different lines
407 on the feeding behavior of *Pieris brassica* larvae. *Entomol Exp Appl* 104:143–151

408 Kaiser HF (1958) Best approximation of a common variance factor space. Working paper,
409 Bureau of Educational Research, University of Illinois, Research Report No. 25

410 Kalabokas P, Hjorth J, Foret G, Dufour G, Eremenko M, Siour G, Cuesta J, Beekmann M
411 (2017) An investigation on the origin of regional springtime ozone episodes in the western
412 Mediterranean. *Atmos Chem Phys* 17:3905–3928

413 Karuppasamy R, Ecanthezhiyan C, Para Sarthi K (2001) Inhibitory effects of *Annona*
414 *squamosa* (Annonaceae) on the digestive enzymes of *Pheropsophus hilaris* (fabr.)
415 (Coleoptera: Carabidae). *Environ Ecol* 19:584–587

416 Koike T (1988) Leaf structure and photosynthetic performance as related to the forest
417 succession of deciduous broad-leaved trees. *Plant Spec Biol* 3:77–87

418 Li P, Feng Z, Calatayud V, Yuan X, Xu Y, Paoletti E (2017) A meta-analysis on growth,
419 physiological, and biochemical responses of woody species to ground-level ozone highlights
420 the role of plant functional types. *Plant Cell Environ* 40:2369–2380

421 Lindroth RL (2010) Impacts of elevated atmospheric CO₂ and O₃ on forests: phytochemistry,
422 trophic interactions, and ecosystem dynamics. *J Chem Ecol* 36:2–21

423 López-Martínez G, Hahn DA (2012) Short-term anoxic conditioning hormesis boosts
424 antioxidant defenses, lowers oxidative damage following irradiation and enhances male
425 sexual performance in the Caribbean fruit fly, *Anastrepha suspensa*. *J Exp Biol* 215:2150–
426 2161

427 López-Martínez G, Carpenter JE, Hight SD, Hahn DA (2016) Anoxia-conditioning hormesis
428 alters the relationship between irradiation doses for survival and sterility in the cactus moth,
429 *Cactoblastis cactorum* (Lepidoptera: Pyralidae). *Flor Entomol* 99:95–104

430 Murdock LL, Brookhart G, Dunn PE, Foard DE, Kelley S (1987) Cysteine digestive
431 proteinases in Coleoptera. *Comp Biochem Physiol* 87B:783787

432 Mead-Hala MIM (2000) New approaches in the control of legumes aphids, *Aphis*
433 *craccisivora* Koch (Homoptera: Aphididae). M.Sc. Thesis, Department of Biological and
434 Natural Sciences Institute of Environmental studies & Research Ain Shams Univ

435 Montella IR, Schama R, Valle D (2012) The classification of esterases: an important gene
436 family involved in insecticide resistance - A Review. Mem Inst Oswaldo Cruz 107:437–449.

437 Nagashima T, Sudo K, Akimoto H, Kurokawa J, Ohara T (2017) Long-term change in the
438 source contribution to surface ozone over Japan. Atmos Chem Phys 17:8231–8246

439 O'Brien RD (1967) Insecticides – action and metabolism. Academic Press New York &
440 London

441 Oppenoorth FJ, van Asperen K (1960) Allelic genes in the housefly producing modified
442 enzymes that cause organophosphate resistance. Science 132:298–299

443 Osman H, Abdel-Hafez H, Khadir A (2015) Comparison between the efficacy of two nano
444 particles and effective microorganisms on some biological and biochemical aspects of
445 *Spodoptera littoralis*. Int J Agr Innov Res 3:2319–1473

446 Park I-K, Lee S-G, Shin S-C, Kim C-S, Ahn Y-J (2004) Feeding and attraction of *Agelastica*
447 *coerulea* (Coleoptera: Chrysomelidae) to Betulaceae plants. J Econ Entomol 97:1978–1982

448 Powell MEA, Smith MJH (1954) The determination of serum acid and alkaline phosphatase
449 activity with 4-aminoantipyrine (A.A.P.). J Clin Pathol 7: 245–248

450 Reiser B, Faraggi D (1999) Confidence intervals for the overlapping coefficient: The normal
451 equal variance case. J Roy Stat Soc 48:413–418

452 Reitman S, Frankel S (1957) A colorimetric method for the determination of serum glutamic
453 oxalacetic and glutamic pyruvic transaminases. Amer J Clin Pathol 28:56–63

454 Ristow M, Schmeisser S (2011) Extending life span by increasing oxidative stress. Free Rad
455 Biol Med 51:327–336

456 Sakikawa T, Oikawa M, Watanabe M, Mao Q, Koike T (2014) The effect of ozone on leaf
457 phenology of white birch (*Betula platyphylla* var. *japonica*) grown under free-air ozone
458 exposure. *Boreal For Res* 62:59–60 (in Japanese)

459 Sakikawa T, Nakamura M, Watanabe M, Oikawa M, Satoh F, Koike T (2016) Leaf
460 phenology and insect grazing of Japanese white birch saplings grown under free-air ozone
461 exposure. *J Agr Meteorol* 72:80–84.

462 Sicard P, Alessandro A, De Marco A, Paoletti E (2017) Projected global tropospheric ozone
463 impacts on vegetation under different emission and climate scenarios. *Atmos Chem Phys*
464 *Discuss* 17:12177–12196.

465 Sogorb MA, Vilanova E (2002) Enzymes involved in the detoxification of
466 organophosphorous, carbamate and pyrethroid insecticides through hydrolysis. *Toxicol Lett*
467 128:215–228.

468 Solomou E, Poupkou A, Bolis S, Zanis P, Lazaridis M, Melas D (2018) Evaluating near-
469 surface ozone levels simulated from MACC global and regional modelling systems in Eastern
470 Mediterranean under the influence of Etesian winds. *Atmos. Res.*
471 <http://dx.doi.org/10.1016/j.atmosres.2017.09.010>

472 Strimbu K, Tavel JA (2010) What are biomarkers? *Curr Opin HIV AIDS* 5: 463–466.

473 Upadhyay R, Jaiswal G. and Ahmed S. (2010). Biochemical and enzymatic alterations after
474 application of fipronil, thiomethoxam and malathion to *Odontotermes obesus*. *Acta Univ Sapi*
475 *Agric Environ* 2:58–79.

476 Tapia PC (2006) Sublethal mitochondrial stress with an attendant stoichiometric
477 augmentation of reactive oxygen species may precipitate many of the beneficial alterations in

478 cellular physiology produced by caloric restriction, intermittent fasting, exercise and dietary
479 phytonutrients: “Mitohormesis” for health and vitality. *Med Hypoth* 66:832–843

480 Telesnicki MC, Martínez-Ghersa MA, Arneodo JD, Ghersa CM (2015) Direct effect of ozone
481 pollution on aphids: revisiting the evidence at individual and population scales. *Entom Exp*
482 *Appl* 155:71–79

483 Telesnicki MC, Martínez-Ghersa MA, Ghersa CM (2018) Plant oxidative status under ozone
484 pollution as predictor for aphid population growth: The case of *Metopolophium dirhodum*
485 (Hemiptera: Aphididae) in *Triticum aestivum* (Poales: Poaceae). *Biochem System Ecol*
486 77:51–56

487 Valkama E, Koricheva J, Oksanen E (2007) Effects of elevated O₃, alone and in combination
488 with elevated CO₂, on tree leaf chemistry and insect herbivore performance: a meta-analysis.
489 *Glob Change Biol* 13:184–201

490 Van Asperen K (1962). A study of housefly esterases by means of a sensitive colorimetric
491 method. *J Ins Physiol* 8:401–416

492 Vanderstock A, Agathokleous E, Inoue W, Eguchi N, Nakamura M, Satoh F, Kanie S, Koike
493 T (2016) Preliminary survey on insect grazing in white birch stands under free-air O₃
494 fumigation. *Boreal For Res* 64:27–29

495 Velasco E, Retama A (2017) Ozone’s threat hits back Mexico city. *Sustain Cit Soc* 31:260–
496 263

497 Wang T, Xue L, Brimblecombe P, Fat Lam Y, Li L, Zhang L (2017) Ozone pollution in
498 China: A review of concentrations, meteorological influences, chemical precursors, and
499 effects. *Sci Tot Environ* 575:1582–1596

500 Wigglesworth VB (2012) *The Principles Of Insect Physiology* . 7th ed. Chapman and Hall Ltd.

501 Wolf FM (1986) *Meta-analysis: Quantitative Methods for Research Synthesis*. Beverly Hills,

502 CA: Sage

503 Wool D, Greenberg S (1990) Esterase activity in whiteflies (*Bemisia tabaci*) in Israel in

504 relation to insecticide resistance. *Entom Exp Applic* 57:251–258

505 Zibae A, Sendi JJ, Etebari K, Alinia F, Ghadamyari M (2009) Characterization of alpha and

506 beta glucosidases in midgut and salivary glands of *Chilo suppressalis* walker (Lepidoptera:

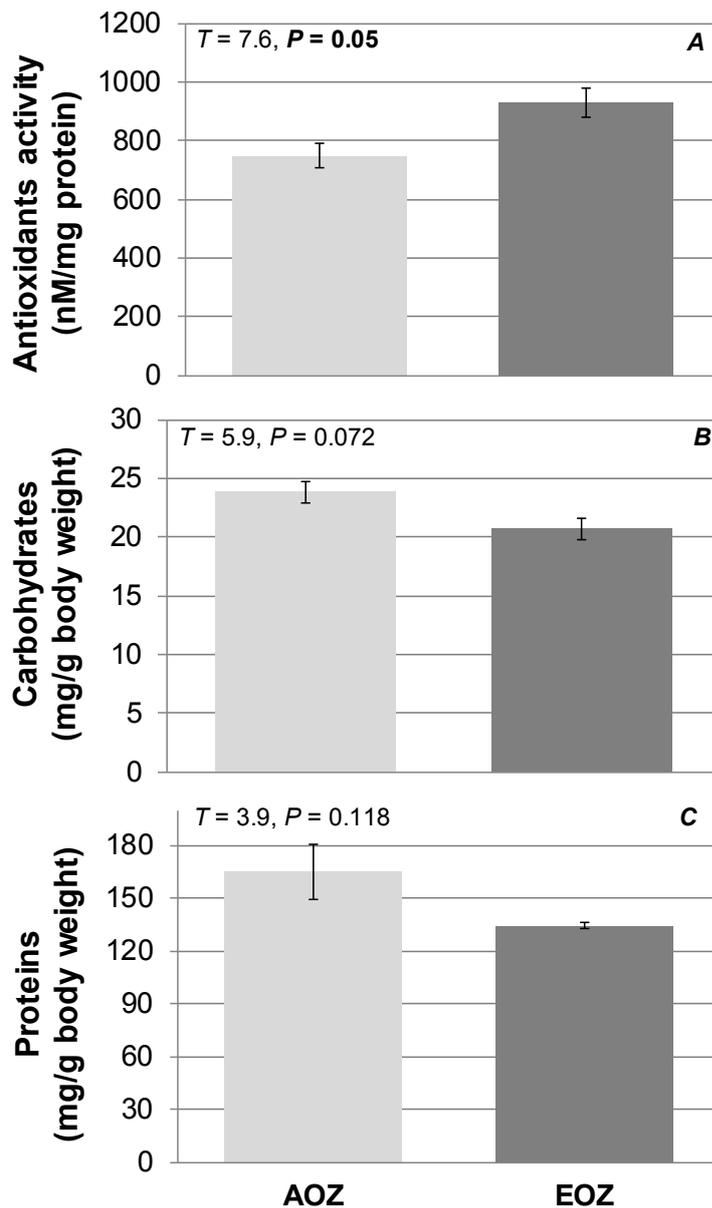
507 Pyraliidae), rice striped stem borer. *Mum Compt Rend Biol* 332:633–641

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510 Fig 1

511 **Fig. 1** The means (\pm SE) of total antioxidant activity (A), total carbohydrate content (B), and
512 total protein content (C) in adult insects of *Agelastica coerulea* in ambient (AOZ) or elevated
513 (EOZ) O₃ conditions. Data were statistically analyzed by the simple contrast AOZ vs. EOZ (n
514 = 3). P -values marked with bold indicate statistical significance at an α level of 0.05.

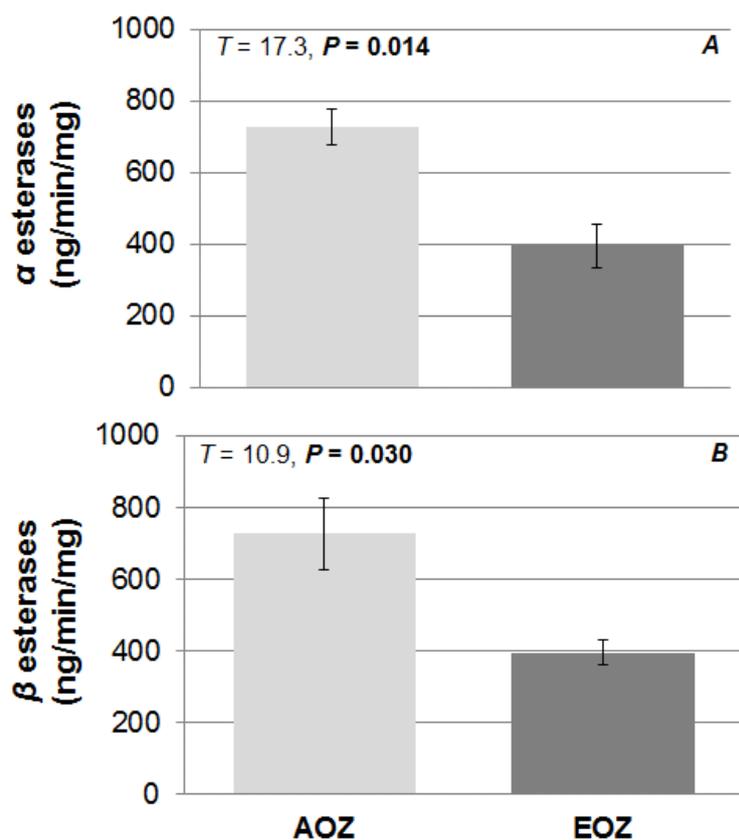


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517 Fig 2

518 **Fig. 2** The means (\pm SE) of alpha (*A*) and beta (*B*) esterases in adult insects of *Agelastica*
519 *coerulea* in ambient (AOZ) or elevated (EOZ) O₃ conditions. The units are ng α -naphthol
520 min⁻¹ mg⁻¹ protein for alpha esterases and ng β -naphthol min⁻¹ mg⁻¹ protein for beta esterases.
521 Data were statistically analyzed by the simple contrast AOZ vs. EOZ ($n = 3$). *P*-values
522 marked with bold indicate statistical significance at an α level of 0.05.

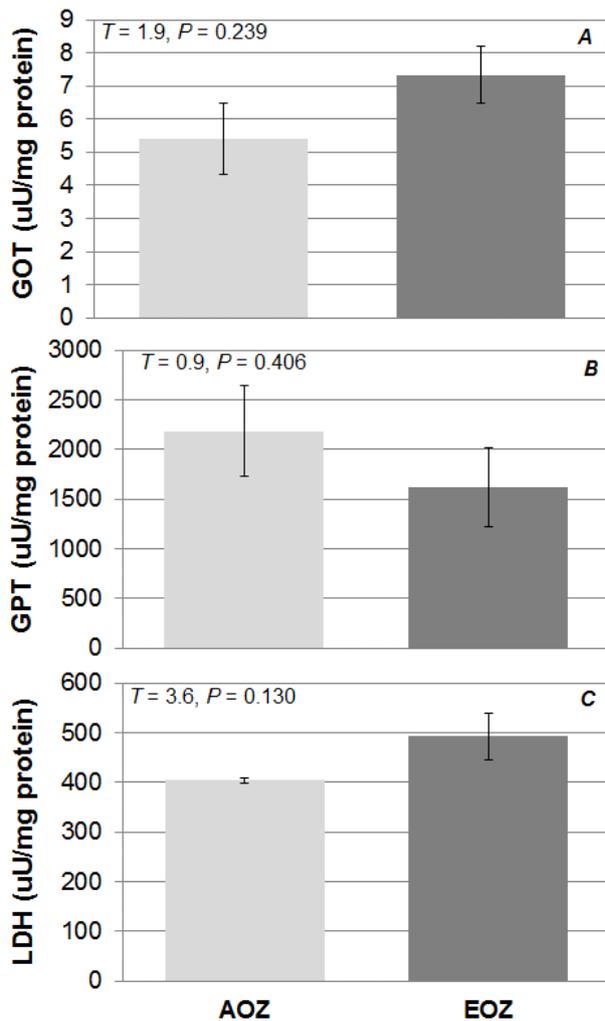


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525 Fig 3

526 **Fig. 3** The means (\pm SE) of glutamic-oxaloacetic transaminase, GOT (A), glutamic-pyruvic
527 transaminase, GPT (B), and lactate dehydrogenase, LDH (C) in adult insects of *Agelastica*
528 *coerulea* in ambient (AOZ) or elevated (EOZ) O₃ conditions. Data were statistically analyzed
529 by the simple contrast AOZ vs. EOZ ($n = 3$), at an α level of 0.05.

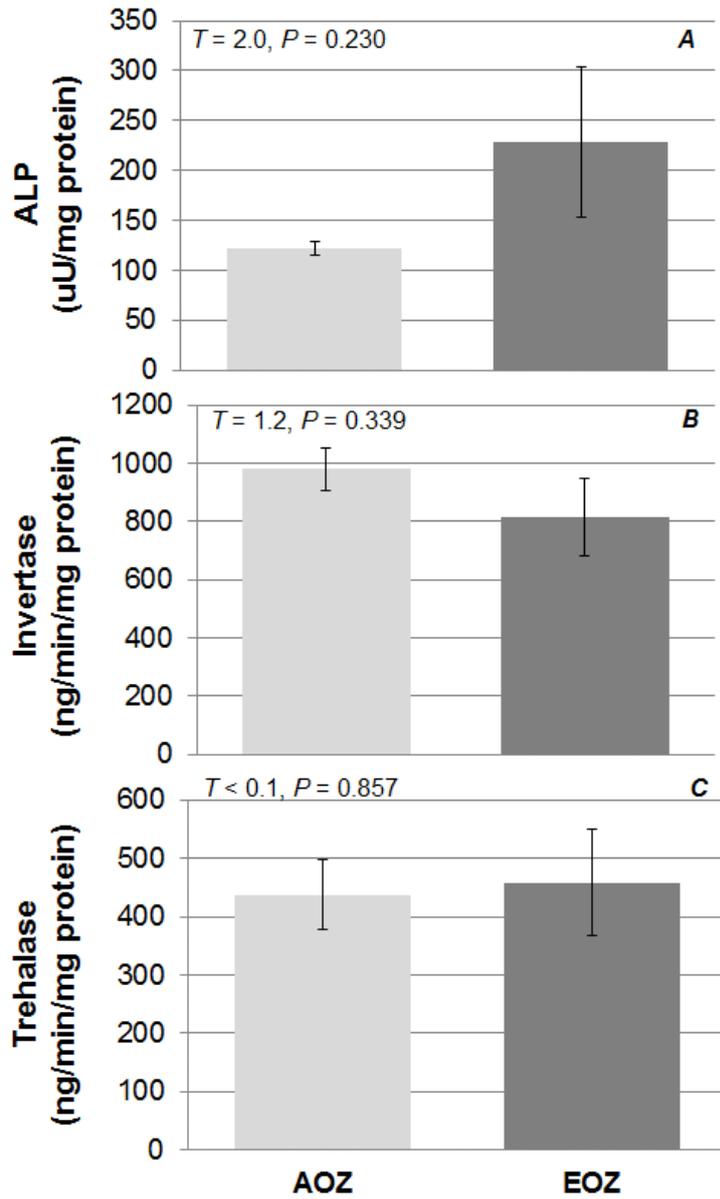


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532 Fig 4

533 **Fig. 4** The means (\pm SE) of alkaline phosphatase, ALP (A), invertase (B), and trehalase (C) in
534 adult insects of *Agelastica coerulea* in ambient (AOZ) or elevated (EOZ) O₃ conditions. Data
535 were statistically analyzed by the simple contrast AOZ vs. EOZ ($n = 3$), at an α level of 0.05.

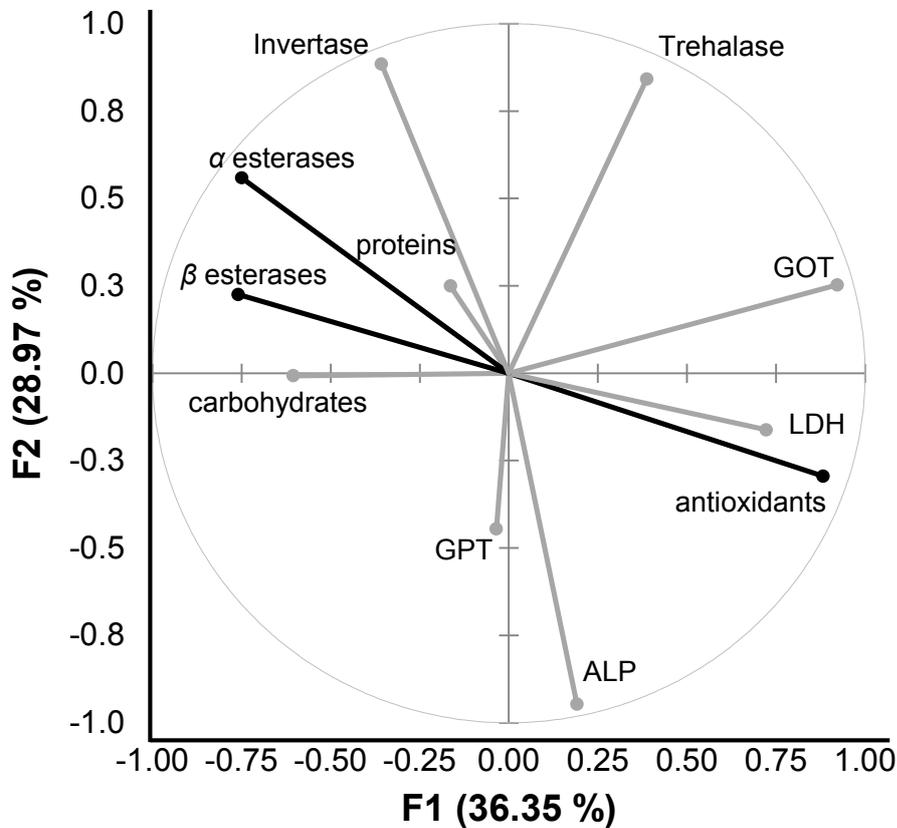


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538 Fig 5

539 **Fig. 5** Biplot of the PCA ordination with varimax rotation based on T-scores of the response
540 variables. Response variables on which elevated O₃ had a statistically significant effect are
541 represented by black lines and markers, whereas those on which elevated O₃ had no
542 statistically significant effect are represented by gray lines and markers. The response
543 variables were: alpha esterases (α esterases), alkaline phosphatase (ALP), beta esterases (β
544 esterases), glutamic-oxaloacetic transaminase (GOT), glutamic--pyruvic transaminase (GPT),
545 invertase, lactate dehydrogenase (LDH), total antioxidants, total carbohydrates, total proteins,
546 and trehalase.



547

548

549 Table 1

550 **Table 1** The factor loading and the contribution of variable (%) after principal components
 551 analysis based on T-scores of the response variables. Response variables on which elevated
 552 O₃ had a statistically significant effect are represented by bold text, whereas those on which
 553 elevated O₃ had no statistically significant effect are represented by non-bold text. The
 554 response variables were: alpha esterases (α esterases), alkaline phosphatase (ALP), beta
 555 esterases (β esterases), glutamic-oxaloacetic transaminase (GOT), glutamic--pyruvic
 556 transaminase (GPT), invertase, lactate dehydrogenase (LDH), total antioxidants, total
 557 carbohydrates, total proteins, and trehalase.

	Factor loadings			Contribution of the variables (%)		
	F1	F2	F3	F1	F2	F3
α esterases	-0.750	0.559	0.178	14.051	9.810	1.160
ALP	0.191	-0.947	-0.129	0.916	28.114	0.613
β esterases	-0.760	0.225	0.480	14.443	1.594	8.452
GOT	0.922	0.253	0.029	21.277	2.003	0.031
GPT	-0.035	-0.446	0.844	0.030	6.228	26.182
Invertase	-0.357	0.884	-0.224	3.195	24.532	1.851
LDH	0.723	-0.162	-0.326	13.064	0.825	3.905
Total antioxidants	0.882	-0.294	-0.285	19.449	2.718	2.984
Total carbohydrates	-0.605	-0.007	0.770	9.153	0.002	21.764
Total proteins	-0.164	0.265	0.946	0.671	1.953	32.887
Trehalase	0.387	0.842	0.068	3.753	22.222	0.170

558

559 Table 2

560 **Table 2** Bivariate correlation (r) values for pairs of response variables. Bold values were different from 0 with a significance level $\alpha = 0.05$,
 561 whereas non-bold values showed non-statistical significance at an α level of 0.05. The response variables were: alpha esterases (α esterases),
 562 alkaline phosphatase (ALP), beta esterases (β esterases), glutamic-oxaloacetic transaminase (GOT), glutamic--pyruvic transaminase (GPT),
 563 invertase, lactate dehydrogenase (LDH), total antioxidants, total carbohydrates, total proteins, and trehalase.

Variables	α esterases	ALP	β esterases	GOT	GPT	Invertase	LDH	Total antioxidants	Total carbohydrates	Total proteins	Trehalase
α esterases	1	-0.7610	0.7205	-0.5069	0.0155	0.7597	-0.7144	-0.8284	0.5266	0.4253	0.0818
ALP	-0.7610	1	-0.4021	-0.0737	0.2396	-0.9138	0.3086	0.4384	-0.1623	-0.3953	-0.6482
β esterases	0.7205	-0.4021	1	-0.7387	0.2954	0.3904	-0.5396	-0.8478	0.8445	0.6779	-0.0285
GOT	-0.5069	-0.0737	-0.7387	1	-0.1018	-0.1397	0.4530	0.7040	-0.5442	-0.0954	0.5497
GPT	0.0155	0.2396	0.2954	-0.1018	1	-0.5253	-0.2121	-0.0835	0.6135	0.6967	-0.4408
Invertase	0.7597	-0.9138	0.3904	-0.1397	-0.5253	1	-0.2454	-0.4648	0.0033	0.0848	0.5331
LDH	-0.7144	0.3086	-0.5396	0.4530	-0.2121	-0.2454	1	0.8670	-0.7092	-0.3927	0.1003
Total antioxidants	-0.8284	0.4384	-0.8478	0.7040	-0.0835	-0.4648	0.8670	1	-0.7921	-0.4680	0.0036
Total carbohydrates	0.5266	-0.1623	0.8445	-0.5442	0.6135	0.0033	-0.7092	-0.7921	1	0.8203	-0.1126
Total proteins	0.4253	-0.3953	0.6779	-0.0954	0.6967	0.0848	-0.3927	-0.4680	0.8203	1	0.2060
Trehalase	0.0818	-0.6482	-0.0285	0.5497	-0.4408	0.5331	0.1003	0.0036	-0.1126	0.2060	1

564