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Acetylcholinesterase activity in muscle tissue of Norway lobster *Nephrops norvegicus*: Importance of body size, season, sex and naturally occurring metals

Arijana Cenov^{a,b}, Dijana Tomić Linšak^{a,b,*}, Lorena Perić^{c,***}, Paula Žurga^{a,d},
 Darija Vukić Lušić^{a,b}, Luka Traven^{a,b}, Željko Linšak^{a,b}, Sandra Marinac Pupavac^a,
 Bojan Hamer^e, Jadranka Pelikan^{a,e}, Marin Glad^{a,b}

^a Teaching Institute of Public Health of Primorje-Gorski Kotar County, Krešimirova 52a, 51000 Rijeka, Croatia

^b Department of Environmental Health, University of Rijeka, Faculty of Medicine, Braće Branchetta 20, 51000 Rijeka, Croatia

^c Division for Marine and Environmental Research, Ruđer Bošković Institute, Bijenička cesta 54, 10000 Zagreb, Croatia

^d Department for Medical Chemistry, Biochemistry and Clinical Chemistry, University of Rijeka, Faculty of Medicine, Braće Branchetta 20, 51000 Rijeka, Croatia

^e Center for Marine Research, Ruđer Bošković Institute, G. Paliaga 5, 52210, Rovinj, Croatia

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ABSTRACT

The aim of the present study was to determine the levels of acetylcholinesterase (AChE) activity in the tail muscle tissue of wild populations of *Nephrops norvegicus* from the Northern Adriatic, and correlate it to body size, seasons, sex and the content of mercury, arsenic, cadmium, lead and copper. The animals of both sexes were collected in spring and autumn from two relatively distant fishing grounds. A marked variability of muscle AChE activity was found (0.49 to 11.22 nmol/min/mg prot.), displaying the opposite seasonal trend between two sampling sites. Small, but significant negative correlation has been found between AChE activity and carapace length ($r_s = -0.35, p < 0.05$). Data reported here provide an essential baseline for future studies of neurotoxicity in crustaceans. The study highlights the necessity for continuous monitoring of potentially toxic metals in edible marine species to avoid possible repercussions of seafood consumption on human health.

1. Introduction

The constantly increasing levels of pollutants introduced from various land-based sources represent serious threats for marine coastal ecosystems. Further intensification of anthropogenic activities and environmental degradation is foreseen in the near future due to human population increase and climate change related to global warming (Cramer et al., 2018). While the adverse effects of chemical pollutants in various marine organisms inhabiting particularly sensitive coastal and estuarine regions have been extensively studied in recent decades (Maulvault et al., 2019; Macleod et al., 2016), less is known on the susceptibility to these compounds of economically and ecologically important organisms in their offshore fishing grounds (Tursi et al., 2015).

The Norway lobster *Nephrops norvegicus* is among the most harvested species and used as a food source throughout the Mediterranean Sea and NE Atlantic. This decapod crustacean is both a predator and a scavenger that predominantly feeds on various small benthic invertebrates and fish (Zacchetti et al., 2022) and could be found even at depths of nearly 800 m (Johnson et al., 2013). Owing to the burrowing lifestyle, *N. norvegicus* may become susceptible to potentially harmful contaminants in the sediment but little is known on how the exposure to these chemicals affect the overall health of this organism (Cenov et al., 2018; Joyce et al., 2023; Stenton et al., 2022). Metals of natural and anthropogenic origin are of particular concern given their ubiquitous distribution, prolonged persistence in the seabed sediments and accumulation in benthic organisms (Komar et al., 2018; Qian et al., 2015).

The stress triggered by exposure to pollutants is quickly manifested

* Corresponding author at: Department for Scientific and Teaching Activity, Teaching Institute of Public Health of Primorje-Gorski Kotar County, Krešimirova 52a, 51000 Rijeka, Croatia.

** Corresponding author at: Department of Environmental Health, University of Rijeka, Faculty of Medicine, Braće Branchetta 20, 51000 Rijeka, Croatia.

*** Corresponding author.

E-mail addresses: dijanatl@uniri.hr (D.T. Linšak), lorena.peric@irb.hr (L. Perić).

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in changes of molecular, biochemical, cellular and physiological functions coupled to maintenance of organisms' homeostasis. These signals serve as biomarkers for early detection of alterations that may eventually lead to irreversible damage at individual, population, and community level (Lagadic, 2002). Well-established standardised biomarkers have been routinely employed in environmental studies as an early diagnostic tool for the health of marine organisms residing in sensitive coastal and estuarine areas (Askem et al., 2018; Frías-Espericueta et al., 2022; Uluturhan et al., 2019) and have also been applied for commercially important species such as *N. norvegicus* (Antó et al., 2009; Carreras-Colom et al., 2022; Stenton et al., 2022). The enzyme acetylcholinesterase (AChE) is a biomarker which takes part in cholinergic transmission by hydrolysing the neurotransmitter acetylcholine into choline and acetic acid. Inhibition of AChE has predominantly been associated with the toxic effect of organophosphorus and carbamate pesticides in a wide range of marine invertebrates (Perić and Burić, 2019; Silva et al., 2019) including crustaceans (Butcherine et al., 2022; Dellali et al., 2021; Oliveira et al., 2013; Taylor et al., 2019). However, AChE in aquatic organisms may as well be affected by metals as shown in several experimental trials with mercury (Hg) in crayfish (Gunderson et al., 2018) and prawns (Harayashiki et al., 2016), cadmium (Cd) in oyster (Moncaleano-Niño et al., 2018) and amphipods (Dellali et al., 2021), lead (Pb) in clam (Bejaoui et al., 2020) and frog (Yologlu and Ozmen, 2015), copper (Cu) in fish (Pereira et al., 2019), mussel (Perić and Burić, 2019) and crab (Oliva et al., 2019) and metalloid arsenic (As) in mussel (Santos et al., 2022) and clam (Freitas et al., 2018). The neurotoxic effect of different metals was also reported for field exposed marine crabs (Capparelli et al., 2019; Rodrigues et al., 2014; van Oosterom et al., 2010) and bivalves (Moleiro et al., 2022; Vázquez-Boucard et al., 2014). Currently, the exact mechanism by which these compounds may interfere with AChE activity is not fully understood or is non-specific, as in case of mercury (Frasco et al., 2007).

AChE features in different tissues of *N. norvegicus* were previously determined and its activity in tail muscle suggested as potentially useful biomarker of neurotoxicity in this crustacean species (Antó et al., 2009; Solé et al., 2006) and applied for health assessment of this benthic species (Carreras-Colom et al., 2022). To correctly evaluate the effect of anthropogenic stressors, a well-detailed knowledge is required on how intrinsic factors modulate the enzymatic activity across seasons and in individuals of different body size and sex.

The present investigation is a part of research looking into natural variations of biological indices in different tissues of wild *N. norvegicus* populations. The aim of this study was to determine the level of AChE activity in *N. norvegicus*, in relation to body size, seasons and sex. Alterations of AChE activity were also linked to body burden of potentially toxic metals (Hg, Cd, Pb, and Cu) and As in the muscle tissue. The results of this study will contribute to a better understanding of factors that may interfere with the evaluation of *N. norvegicus* health status by analyses of AChE activity during ecotoxicological risk assessment activities. This data will also upgrade currently available information on the safety of end consumers associated to exposure of *N. norvegicus* to metals in their habitats within Northern Adriatic offshore areas.

2. Materials and methods

2.1. Description of sampling locations

Two sampling sites within fishing grounds of the semi-enclosed Kvarner Bay (Northern Adriatic, Croatia) have been selected for this investigation (Fig. 1). The first sampling site S1 was positioned in the innermost part of the bay, at the distance of approximately 8–11 km from the city of Rijeka. The location of the second sampling site S2 was approximately 70 km south of Rijeka. Level of pollutants at the two offshore sampling sites is currently unknown. In general, concentration of various chemical pollutants may vary considerably along the coast of the Kvarner Bay, with the highest values recorded in the near-shore

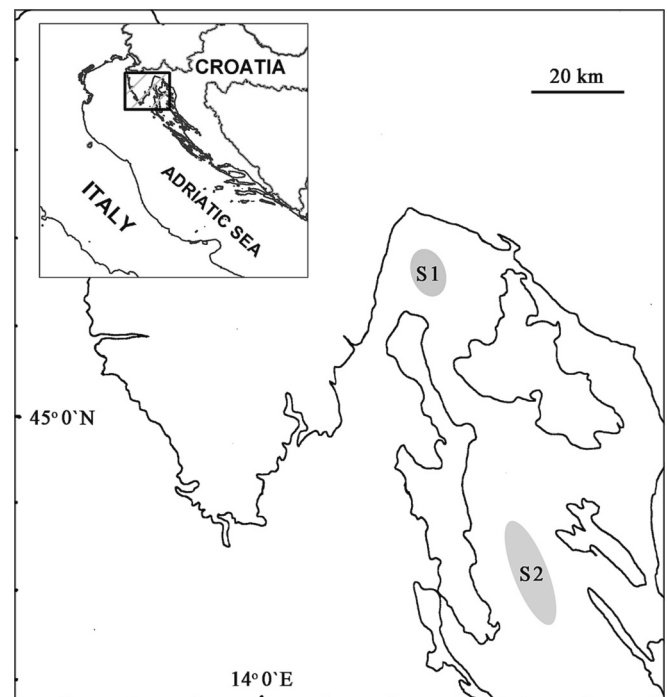


Fig. 1. Map of sampling sites in the Northern Adriatic.

sediments and biota next to industrial sites that are substantially reduced with an increasing distance from pollution sources (Bihari et al., 2007; Cukrov et al., 2011, 2014; Fafandel et al., 2015; Perić et al., 2012). However, enrichment of sediments with mercury discharged from industrial sites and inland deposits was recorded on several occasions over wider areas of the Northern Adriatic (Covelli et al., 2011; Fitzgerald et al., 2007; Kotnik et al., 2015). Commercial fishing grounds that encompass both sampling sites are close to traditional routes for commercial vessels including oil tankers and numerous touristic boats.

N. norvegicus samples were collected in autumn 2014 and spring 2015 by trawl fishing gear from the bottom at depths of 55–62 m (S1) and 70–78 m (S2). Following collection, the organisms were immediately inspected to select the healthy individuals without any signs of external damage. Males were discerned from females by increased thickness and higher rigidity of the first pair of abdominal swimmerets. The length between eye socket and carapace mid hind edge (carapace length, CL) was recorded for each individual. From each site, 72 individuals characterised by balanced sex ratio and heterogeneous length (Table 1) were dissected to obtain the tail muscle tissue for further analyses. Tissue samples were immediately frozen in liquid nitrogen and stored at -80°C .

2.2. Acetylcholinesterase activity

For acetylcholinesterase activity (AChE) analyses, a portion of tail muscle tissue was homogenized in 1:3 w/V of ice-cold 50 mM phosphate

Table 1
Carapace length values (mm) for *N. norvegicus* from sampling sites S1 and S2.

Site	Season	Sex	Avg	Min–Max	Median
S1	Aut	F (n = 18)	42.8 ± 9.0	30.8–57.2	43.5
		M (n = 18)	45.3 ± 10.1	31.2–61.1	46.1
	Spr	F (n = 18)	36.8 ± 7.3	26.2–47.2	38.0
		M (n = 18)	42.2 ± 11.3	26.8–58.6	44.8
S2	Aut	F (n = 18)	35.8 ± 6.1	27.9–49.1	36.4
		M (n = 18)	40.4 ± 5.8	32.6–53.4	40.6
	Spr	F (n = 18)	39.2 ± 8.0	26.8–52.8	39.5
		M (n = 18)	42.7 ± 8.4	30.5–57.6	41.9

buffer (pH 7.4) using a Teflon homogenizer. Homogenates were centrifuged for 30 min at 4 °C and 10,000 x g, after which the pellets were discarded, and the supernatants kept for further analyses. AChE activity was measured by the method of Bocquené and Galgani (1998). Diluted samples (50 µl) and 200 µl of 5,5-dithio-bis-2-nitrobenzoate solution (DTNB; 300 µM final) were added into micro plate wells. The enzymatic reactions in the wells were started by addition of substrate acetylcholine (ATC, 1 mM final). Measurements of enzymatic activity were carried out by recording the absorbance change at 405 nm occurring upon formation of coloured thionitrobenzoate anion, using a microplate reader (Lab-systems, Multiscan Ascent® and Ascent Software TM, 2.4. version). All samples were analysed in triplicates. Reaction of thiols with DTNB and spontaneous hydrolysis of substrate were determined in the absence of substrate and sample, respectively, and used for correction of absorbance change. The enzymatic activity in the sample was expressed as nmol of hydrolysed substrate per minute and mg of proteins. Concentrations of proteins in the samples were determined by the method of Bradford (1976) with bovine serum albumin as the standard.

2.3. Concentration of metals and arsenic in the muscle tissues

Muscle tissue samples were processed for metal analyses as described in Cenov et al. (2018). Briefly, subsamples of freeze-dried muscle (0.5 g dry weight) were microwave digested (Anton Paar Multivawe 3000, Perkin Elmer, USA) in 65 % nitric acid (HNO₃, Suprapur, Merck, Germany). Digested samples were diluted with ultrapure water (Siemens) and analysed for mercury (Hg), arsenic (As), cadmium (Cd), lead (Pb) and copper (Cu). With exception of Hg, all the analyses were carried out with inductively coupled plasma mass spectrometer (ICP MS NexION 300×) equipped with S10 autosampler (Perkin Elmer, USA). Analyses of Hg were performed with atomic absorption spectrometer (AMA 254, Advanced Mercury Analyser, Leco, USA). For analytical quality assurance, the appropriate blanks and certified reference materials were used, whereas the analyses were performed in triplicates. Method for measurement of As, Cd, Pb and Cu was validated with IAEA-407 (fish tissue; International Atomic energy Agency, Austria) and the mean recovery was between 89 % and 110 %. Metals were analysed according to the modified European standard methods EN 14084:2003 and EN 13804:2013. Furthermore, Pb and Cd were included into the accreditation scope of Croatian accreditation agency (Accreditation certificate 1127). NIST 2976 (mussel tissue, National Institute of Standards and Technology, USA) was used for validation of Hg measurements (mean recovery 104 %).

The concentrations in muscle tissue were expressed as µg/g dry weight (d.w.). A dry-to-weight conversion factor of five was used to express the wet weight (w.w.), based on the weight difference between wet and freeze-dried samples, indicating that the average proportion of moisture content in the tissue was equal to 80 % (Cresson et al., 2014; Mille et al., 2018).

2.4. Data processing

Shapiro-Wilk and Levene's test were used to verify the normality and homogeneity of data, respectively. For testing of difference between the responses of two groups by Student's *t*-test, data for AChE activity corresponding to each tested group were log transformed to achieve normality. Since the normality assumption across variables could not be met by transformation operation, correlations were determined using the non-parametric Spearman's rank correlation analysis. The significance level was set to $p < 0.05$. All statistical analyses were carried out using RStudio software, version 1.0.153 (RStudio Team, 2017).

3. Results and discussion

The activity of acetylcholinesterase (AChE) in the muscle of *Nephrops*

norvegicus for two sites, seasons and sex, is shown in Fig. 2. The values for AChE activity at sites S1 and S2 ranged between 0.49 and 11.22 and 0.64 and 9.71 nmol/min/mg of proteins, respectively, and were generally in line to those previously reported for muscle tissue of *N. norvegicus* from NW Mediterranean (Antó et al., 2009; Carreras-Colom et al., 2022; Solé et al., 2006).

Natural variability of AChE activity in marine invertebrates has been associated to seasonal fluctuations of environmental and biotic factors, including the reproductive cycle (Capparelli et al., 2019; Perić and Petrović, 2011; Ramos et al., 2016). Considering that the reproductive activity of *N. norvegicus* in the Mediterranean intensifies during spring to summer period and becomes suppressed in autumn (Aguzzi and Sardà, 2008; Orsi Relini et al., 1998) a strong seasonality of AChE activity was expected. Results of previous study on AChE activity changes in the muscle tissue of *N. norvegicus* over different seasons were inconclusive due to a low number and unbalanced sex ratio of individuals (Antó et al., 2009). In the present work, a larger sample size containing equal number of males and females allowed detection of the opposite, site-dependent seasonal patterns. At site S1, the enzymatic activity was significantly higher in autumn in female lobsters only ($t(34) = 3.34, p < 0.01$), while at S2 significantly higher AChE activity was recorded in spring in both males ($t(34) = -4.29, p < 0.001$) and females ($t(34) = -0.32, p < 0.01$) (Fig. 2). This contrasting seasonal trend for two sampling fishing grounds indicates the influence of local, site-related factors that could have modulated the enzyme activity in spatially distant populations. Previous studies reported that the enrichment with metals in the investigated region was in line with other off-shore regions of the Adriatic Sea (Cukrov et al., 2011, 2014).

The differences in AChE activity between males and females were significant only in autumn at site S2 ($t(34) = 2.72, p < 0.05$) (Fig. 2). In the study of Solé et al. (2006), a reduced AChE activity in *N. norvegicus* females was recorded in spring and was explained by sex-dependent specificities of hormonal status during the period of intensive reproductive activity. Contrastingly, in the present work, males displayed reduced AChE activity with respect to females, and this effect was seen only in autumn, following the peak of reproductive season in the Adriatic (Orsi Relini et al., 1998; Marković et al., 2016). The inconsistency between the two studies and the inability to discern a clear sex-related AChE activity pattern of sampled *N. norvegicus* could have resulted

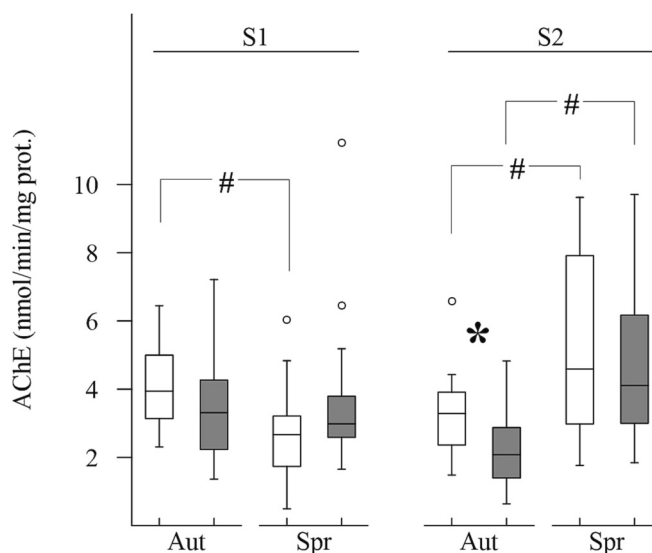


Fig. 2. Acetylcholinesterase activity (AChE) in the tail muscle of female (□) and male (■) Norway lobsters *Nephrops norvegicus* from sites S1 and S2 in the Northern Adriatic in Autumn (Aut) and Spring (Spr). Significant differences ($p < 0.05$) between sex and seasons are indicated by asterisks and hashes, respectively.

from a well-known reproductive cycle asynchrony of this species (Marković et al., 2016; Orsi Relini et al., 1998; Sardà, 1995). The maturation stage of gonads was not investigated in this study, except of visual inspection of sampled organisms that revealed 22 and 30 % of females bearing a mature ovary on their abdomen in spring and autumn, respectively. In addition, considering the role of AChE in cholinergic neurotransmission, differences in the activity of AChE observed between females and males, might also reflect a sex-related specificities of behaviour, such as locomotion, feeding or burrowing activity. For instance, *N. norvegicus* females displayed a reduced emergence period in comparison to males, for better predator protection and variable dynamics of food intake over reproductive cycle (Aguzzi et al., 2007). This issue requires further investigation.

Mild but significant negative correlation of AChE with carapace length ($r_s = -0.35, p < 0.05$) (Table 2) is in concordance with previous reports for *N. norvegicus* from NW Mediterranean coast (Antó et al., 2009; Solé et al., 2006). These results might suggest alterations and remodelling of neuromuscular system or physiological requirements over different life stages as previously described for crustaceans (Atwood, 1992). The moulting process, when old exoskeleton is discarded and new one of increased size is formed, determines the development, growth and concomitant innervation of lobster muscle tissue (Govind, 1992). Thus, more intensive moulting frequency typically seen in young *N. norvegicus*, could explain somewhat higher AChE activity in individuals of lower body size. In addition, changes of cell surface to volume ratio naturally occurring during growth that affect cells metabolism, fitness and functionality (Bodenstein et al., 2023; Hermaniuk et al., 2021; Miettinen et al., 2017) could be hypothesised as another factor involved in AChE activity modulation across various life stages.

Alternatively, lower AChE activity measured in larger *N. norvegicus* samples could also be an indication of longer exposure to contaminants in their habitat. Of all potentially toxic metals analysed here, only mercury (Hg) was significantly, albeit mildly, correlated to AChE activity ($r_s = -0.32, p < 0.05$) (Table 2). The sensitivity and susceptibility of AChE to Hg is species-specific (Frasco et al., 2007) and pieces of evidence for Hg inhibitory effect in crustacean species are still relatively rare. However, an inhibition of AChE activity after Hg exposure was previously reported for muscle tissue of tiger prawn *Penaeus monodon* (Harayashiki et al., 2018) and signal crayfish *Pacifastacus leniusculus* (Gunderson et al., 2018). Neurotoxic AChE inhibitory effect of Hg was also observed in fish (Araújo et al., 2018; Barboza et al., 2018).

As shown in Table 2, Hg displayed a strong and significant positive correlation to body size ($r_s = 0.80, p < 0.05$), with the best fit for the relationship obtained using the power fit equation $\ln(\text{carapace length}) = 0.3025612208 * \ln(\text{Hg concentration}) + 3.265349541, R^2 = 0.62$ (Fig. 3), indicating that its accumulation in *N. norvegicus* increases with age. This is consistent with previous reports for *N. norvegicus* (Barghigiani et al., 2000; Canli and Furness, 1993; Capelli et al., 2004; Di Lena et al., 2018). The average content of $4.63 \pm 2.75 \mu\text{g Hg/g d.w.}$ found in the muscle tissue (Table 3) was comparable to the levels previously established for Central Adriatic (Di Lena et al., 2018; Perugini et al., 2009), and higher than in samples from Tyrrhenian sea (Di Lena et al., 2018), NW Mediterranean area (Cresson et al., 2014) and in particular from Atlantic coasts (Canli and Furness, 1993; Lourenço et al.,

Table 2

Spearman's correlation coefficients (r_s) between AChE, metals and carapace length (CL) in *N. norvegicus* from the Northern Adriatic. Bold values denote statistical significance at the $p < 0.05$ level.

	Hg	As	Cd	Pb	Cu	CL
AChE	-0.32	-0.16	-0.10	-0.36	-0.24	-0.35
Hg		0.33	-0.17	0.05	0.14	0.80
As	0.32		-0.10	-0.36	-0.24	0.34
Cd	-0.18	-0.10		0.42	0.11	-0.11
Pb	0.05	-0.36	0.42		0.36	0.04
Cu	0.14	-0.24	0.11	0.35		0.09

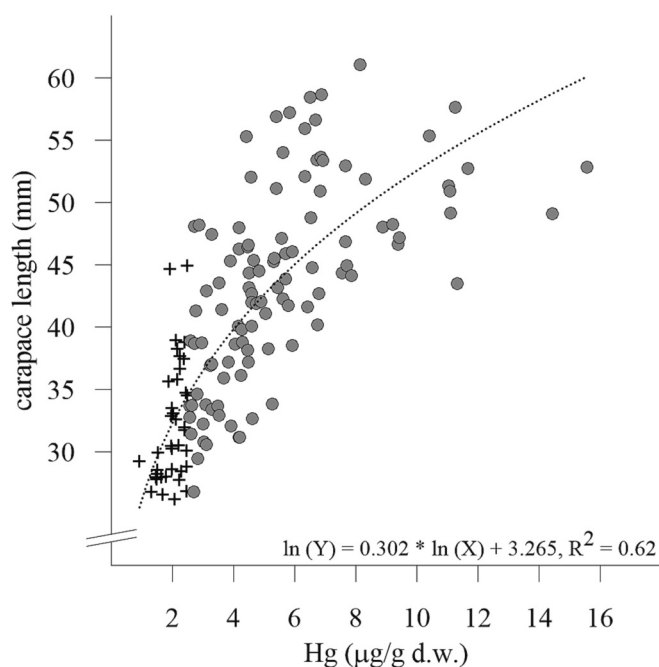


Fig. 3. Relation between carapace length (mm) and mercury concentration ($\mu\text{g/g d.w.}$) in the tail muscle of Norway lobster *Nephrops norvegicus* ($N = 144$). Dashed line denotes the power – fit. Symbols indicate samples with Hg levels of $\geq 0.5 \mu\text{g/g w.w.}$ (●) and $< 0.5 \mu\text{g/g w.w.}$ (+) when a dry-to-wet tissue conversion factor of 5 is used (Cresson et al., 2014; Mille et al., 2018).

2009) and North Sea (Wiech et al., 2021).

Bioaccumulation of Hg over longer period is typically associated with demersal and predatory pelagic fish and marine mammals (Delgado-Suarez et al., 2023; Erasmus et al., 2022). However, relatively high Hg concentrations with respect to other marine areas that were found in muscle tissue indicate that *N. norvegicus* in the Northern Adriatic Sea could be exposed to an elevated background level of Hg in sediment surface related to long-term riverine input and dispersal from Hg mining (Covelli et al., 2011; Fitzgerald et al., 2007; Kotnik et al., 2015).

The concentrations of Hg in the muscle of *N. norvegicus* were in agreement with those previously reported for digestive gland tissue (Cenov et al., 2018). Moreover, a positive correlation of Hg with metallothioneins, the key proteins that participate in metal detoxification and storage in digestive gland, was determined as well (Cenov et al., 2018). These findings, together with the current results, might suggest the occurrence of physiological stress in *N. norvegicus* caused by Hg exposure in their immediate environment. The ecological consequences at higher level of biological organisation could be also anticipated, based on correlations between AChE inhibition and behavioural impairments previously observed in decapod crustaceans after exposure to Hg (Harayashiki et al., 2016) or organic chemicals (Mesquita et al., 2011).

In this study, arsenic (As) was the most abundant element, displaying concentrations in the range between 49.40 and 280.13 $\mu\text{g/g d.w.}$ (Table 3). These values were slightly higher than those reported previously for tail muscle of *N. norvegicus* from the same fishing area in the Northern Adriatic (Klarić et al., 2004; Sekulić et al., 1993), Central Adriatic (Visciano et al., 2013) and Southern Adriatic (Storelli and Marcotrigiano, 2001). Inactivation of AChE by arsenic (As) was previously demonstrated in laboratory experiments with bivalve mussels (Chakraborty et al., 2013; Freitas et al., 2018). It was also reported that decreased AChE activity found in mud crab *Scylla serrata* from a riverine estuary could be associated to high total As burden (van Oosterom et al., 2010). Nevertheless, while As concentrations in the muscle of *N. norvegicus* were also positively correlated to body length ($r_s = 0.34, p$

Table 3

Concentrations of total mercury (tHg), arsenic (As), cadmium (Cd), lead (Pb) and copper (Cu) (mean \pm s.d., $\mu\text{g/g}$ d.w.) in the white tail muscle of *Nephrops norvegicus* from different locations in the Mediterranean Sea and Atlantic Ocean. Range of concentrations is indicated in parenthesis (where available). Asterisks indicate values originally reported on a wet weight basis and recalculated using dry-to-wet conversion factor five (Cresson et al., 2014; Mille et al., 2018); Hashes indicate maximum values.

Location	tHg	As	Cd	Pb	Cu	Reference
Mediterranean Sea	4.63 \pm 2.75 (0.92–15.57)	112.31 \pm 42.29 (49.40–280.13) (26.85–106.95*)	0.08 \pm 0.07 (<0.001–0.41)	0.29 \pm 0.33 (0.04–2.74)	21.37 \pm 5.93 (5.09–51.52)	present work
Northern Adriatic	5.985 \pm 2.30* (2.735–11.705*) 4.85 \pm 4.35* (1.45–16.35*)	(85.55 \pm 22.40*)	0.05 \pm 0.05*	0.05 \pm 0.05*		Sekulić et al., 1993 Klarić et al., 2004 Di Lena et al., 2018 Perugini et al., 2009
Central Adriatic		80.45 \pm 3.05* 121.9* 43.48 \pm 14.21 (35.63–69.15)	<0.05*	0.185*	22.15*	Perugini et al., 2014 Visciano et al., 2013 Iamiceli et al., 2015 Storelli and Marcotrigiano, 2001
Southern Adriatic		270*	<0.05*	0.16*	20.5*	Iamiceli et al., 2015 Di Lena et al., 2018
Thyrenian Sea	1.345 \pm 0.60* (0.69–3.05*)		0.336 \pm 0.266 (0.030–0.630)	0.138 \pm 0.136 (0.04–0.350)	61.9 \pm 25.1 (30.2–93.1)	Mille et al., 2018 Cresson et al., 2014
Gulph of Lyons	1.80 \pm 0.97 4.14# 2.55*		0.150*		27.35*	Capelli et al., 2004
Ligurian Sea	0.6–8.5*		0.015–0.755*		10.75–83.10*	
Atlantic Ocean			0.10 \pm 0.05 (0.040–0.160)	0.124 \pm 0.038 (0.100–0.190)	12.6 \pm 4.7 (8.2–18.4)	Mille et al., 2018
Bay of Biscay			1.74 \pm 0.71	1.70 \pm 2.07	26.0 \pm 9.0	Canli and Furness, 1993
West Scotland	0.60 \pm 0.30 2.0 \pm 0.8*		0.50 \pm 0.2*	0.25 \pm 0.05*	53.0 \pm 11.0*	Lourenço et al., 2009
SW Portugal	(1.05–3.65*)		(0.15–0.75*)	(0.2–0.3*)	(41.0 \pm 77.5*)	Wiech et al., 2021
West Norway	0.5 \pm 0.25* (0.13–1.45*)					

< 0.05), no correlation with AChE activity was detected (Table 2) possibly because the percentage of inorganic As, which represents the more toxic form of As (Ventura-Lima et al., 2011), was low with respect to the total As. The exact ratio of As forms in the muscle tissue was not evaluated in this study, however it was previously shown that inorganic As in the *N. norvegicus* tail muscle from Southern Adriatic Sea accounts for <10 % of the total As (Storelli and Marcotrigiano, 2001). It could be also speculated that *N. norvegicus* AChE may not contain structural features required for As binding and subsequent inactivation (Ventura-Lima et al., 2011).

The levels of cadmium, lead and copper in the muscle of *N. norvegicus* were generally in the same order of magnitude as those previously reported for other Mediterranean and Atlantic coastal regions (Table 3) and none of these metals displayed correlations with AChE activity (Table 2). This result could suggest that concentrations of these metals were too low to create an effect on AChE and that these compounds are consequently of little relevance for muscle AChE activity fluctuations in *N. norvegicus* from the Northern Adriatic.

Anthropogenic activity in coastal areas usually produces rather complex mixture of pollutants in marine ecosystems. Therefore, it is plausible that the ability to discern a clearer pattern of AChE activity was limited by the presence of other types of pollutants, not assessed in this study. Pesticides containing organophosphates and carbamates as active ingredient are commonly applied for pest control in agricultural fields, from where these compounds may be delivered to coastal zones by run-offs, riverine input and air deposition and then transferred from water column to sediments (Triassi et al., 2019).

Organophosphorous and carbamate pesticides reportedly inhibited AChE activity in various crustaceans (Bertrand et al., 2016; Oliveira et al., 2013; Taylor et al., 2019). Nevertheless, the landscapes adjacent to sampling sites have contained agricultural activity of low intensity

and the levels of pesticides in environmental matrices sampled from Northern Adriatic offshore locations are yet to be confirmed. AChE activity modulation in crustaceans and other invertebrates was also linked to other classes of marine pollutants, such as polybrominated diphenyl ether (Chen et al., 2015), various antifoulants (Lee et al., 2017) and herbicides (Juhel et al., 2017).

High Hg content detected in *N. norvegicus* muscle tissue raises questions on the overall safety for its consumption. By using a dry-to-wet tissue conversion factor of 5, the mean total Hg concentration of 4.68 $\mu\text{g/g}$ d.w. determined in this study is converted to the value of 0.93 $\mu\text{g/g}$ w.w. that is almost two-fold above the maximum level of 0.5 $\mu\text{g/g}$ w.w. in foodstuff as set by EU standards (EC, 2006). Moreover, the value has been exceeded in >75 % of individuals (Fig. 3).

One previous study indicated that frequent consumption of *N. norvegicus* captured at some presumed Hg hot spots in the Adriatic might not be safe since the EU threshold level of total Hg content was exceeded in virtually all samples of *N. norvegicus* muscle (Di Lena et al., 2018). Thus, it is essential to carry on with investigations in the Adriatic in order to gain more knowledge on the Hg content in *N. norvegicus* and increase public awareness of the risks associated to its consumption (Di Lena et al., 2018; Perugini et al., 2009).

4. Conclusions

In this study, the range of AChE activity was determined in the muscle of *Nephrops norvegicus* from two fishing grounds in the Northern Adriatic. In the present study differences in baseline AChE activity with respect to season and sex were determined. Most importantly, careful selection of individuals of homogeneous body size is needed to increase the power and reliability of AChE activity evaluation. The present data indicate that benthic organisms in the Northern Adriatic may be exposed

to natural, but relatively high background levels of Hg raising concerns for possible adverse effects in wild caught *N. norvegicus*. However, controlled laboratory experiments using individuals of varying length and age are needed to verify the influence of Hg on AChE activity in *N. norvegicus* muscle. Full discrimination potential of AChE activity in the muscle of *N. norvegicus* should be evaluated by examination of organisms collected from regions with contrasting levels of metals. Finally, this study underlines the importance of continuous monitoring in order to evaluate Hg availability trends and the overall safety of seafood consumption.

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Ethical statement

This work did not require institutional ethical review or approval.

CRediT authorship contribution statement

Arijana Cenov: Writing – original draft, Methodology, Investigation. **Dijana Tomić Linšak:** Writing – review & editing, Supervision. **Lorena Perić:** Writing – original draft, Conceptualization. **Paula Žurga:** Validation, Methodology, Formal analysis. **Darija Vukić Lušić:** Visualization, Conceptualization. **Luka Traven:** Software, Data curation. **Željko Linšak:** Resources, Investigation. **Sandra Marinac Pupovac:** Validation, Methodology. **Bojan Hamer:** Resources, Conceptualization. **Jadranka Pelikan:** Methodology, Investigation. **Marin Glad:** Visualization, Supervision, Software, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships which could influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- Aguzzi, J., Sardà, F., 2008. A history of recent advancements on *Nephrops norvegicus* behavioral and physiological rhythms. *Rev. Fish Biol. Fisher.* 18 (2), 235–248. <https://doi.org/10.1007/s11160-007-9071-9>.
- Aguzzi, J., Company, J.B., Sardà, F., 2007. The activity rhythm of berried and unberried females of *Nephrops norvegicus* (Decapoda, Nephropidae). *Crustaceana* 80 (9), 1121–1134. <https://doi.org/10.1163/156854007782008577>.
- Antó, M., Arnau, S., Buti, E., Cortijo, V., Gutiérrez, E., Solé, M., 2009. Characterisation of integrated stress biomarkers in two deep-sea crustaceans, *Aristeus antennatus* and *Nephrops norvegicus*, from the NW fishing grounds of the Mediterranean Sea. *Ecotox. Environ. Saf.* 72 (5), 1455–1462. <https://doi.org/10.1016/j.ecoenv.2009.02.007>.
- Araújo, M.C., Assis, C.R.D., Silva, K.C.C., Souza, K.S., Azevedo, R.S., Alves, M.H.M.E., Silva, L.C., Silva, V.L., Adam, M.L., Carvalho Junior, L.B., Souza Bezerra, R., Oliveira, M.B.M., 2018. Characterization of brain acetylcholinesterase of benthic fish *Hoplosternum littorale*: perspectives of application in pesticides and metal ions biomonitoring. *Aquat. Toxicol.* 213–226 <https://doi.org/10.1016/j.aquatox.2018.10.017>.
- Askem, C.E., Wright, S.R., Vannoni, M., Robinson, C.D., White, K., Lyons, B.P., Nicolaus, E.E.M., 2018. Spatial and temporal analysis of biliary 1-hydroxypyrene, hepatic ethoxyresorufin-O-deethylase and muscle acetylcholinesterase activity in UK flatfish. *Mar. Pollut. Bull.* 133, 872–880. <https://doi.org/10.1016/j.marpolbul.2018.06.059>.
- Atwood, H.L., 1992. Age-dependent alterations of synaptic performance and plasticity in crustacean motor systems. *Exp. Gerontol.* 27 (1), 51–61. [https://doi.org/10.1016/0531-5565\(92\)90028-X](https://doi.org/10.1016/0531-5565(92)90028-X).
- Barboza, L.G.A., Vieira, L.R., Branco, V., Figueiredo, N., Carvalho, F., Carvalho, C., Guilhermino, L., 2018. Microplastics cause neurotoxicity, oxidative damage and energy-related changes and interact with the bioaccumulation of mercury in the European seabass, *Dicentrarchus labrax* (Linnaeus, 1758). *Aquat. Toxicol.* 195, 49–57. <https://doi.org/10.1016/j.aquatox.2017.12.008>.
- Barghigiani, C., Ristori, T., Biagi, F., De Ranieri, S., 2000. Size related mercury accumulations in edible marine species from an area of the northern Tyrrhenian Sea. *Water Air Soil Poll.* 124 (1–4), 169–176. <https://doi.org/10.1023/A:1005252504734>.
- Bejaoui, S., Telahigue, K., Chetoui, I., Trabelsi, W., Rabeh, I., Nechi, S., Chalbi, E., Chalhaf, M., Cafi, M.E.L., Soudani, N., 2020. Effects of lead exposure on redox status, DNA and histological structures in *Venus verrucosa* gills and digestive gland. *Chem. Ecol.* 36 (5), 434–457. <https://doi.org/10.1080/02757540.2020.1742329>.
- Bertrand, L., Monferrán, M.V., Mouneyrac, C., Bonansea, R.I., Asis, R., Amé, M.V., 2016. Sensitive biomarker responses of the shrimp *Palaemonetes argentinus* exposed to chlorpyrifos at environmental concentrations: roles of alpha-tocopherol and metallothioneins. *Aquat. Toxicol.* 179, 72–81. <https://doi.org/10.1016/j.aquatox.2016.08.014>.
- Bihari, N., Fafandel, M., Piškur, V., 2007. Polycyclic aromatic hydrocarbons and ecotoxicological characterization of seawater, sediment, and mussel *Mytilus galloprovincialis* from the Gulf of Rijeka, the Adriatic Sea. *Croatia. Arch. Environ. Con. Tox.* 52 (3), 379–387. <https://doi.org/10.1007/s00244-005-0259-5>.
- Bocquené, G., Galgani, F., 1998. Biological Effects of Contaminants: Cholinesterase Inhibition by Organophosphate and Carbamate Compounds. *ICES Tech. Mar. Environ. Sci.*, p. 22.
- Bodenstein, S., Callam, B.R., Walton, W.C., Rikard, F.S., Tiersch, T.R., La Peyre, J.F., 2023. Survival and growth of triploid eastern oysters, *Crassostrea virginica*, produced from wild diploids collected from low-salinity areas. *Aquaculture* 564, 739032. <https://doi.org/10.1016/j.aquaculture.2022.739032>.
- Bradford, M.M., 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal. Biochem.* 72, 248–254.
- Butcherine, P., Kelaher, B.P., Benkendorff, K., 2022. Assessment of acetylcholinesterase, catalase, and glutathione S-transferase as biomarkers for imidacloprid exposure in penaeid shrimp. *Aquat. Toxicol.* 242, art. no. 106050 <https://doi.org/10.1016/j.aquatox.2021.106050>.
- Canli, M., Furness, R.W., 1993. Toxicity of heavy metals dissolved in sea water and influences of sex and size on metal accumulation and tissue distribution in the Norway lobster *Nephrops norvegicus*. *Mar. Environ. Res.* 36 (4), 217–236. [https://doi.org/10.1016/0141-1136\(93\)90090-M](https://doi.org/10.1016/0141-1136(93)90090-M).
- Capelli, R., Drava, G., Siccardi, C., De Pellegrini, R., Minganti, V., 2004. Study of the distribution of trace elements in six species of marine organisms of the Ligurian Sea (South-western Mediterranean) - comparison with previous findings. *Ann. Chim. Rome* 94 (7–8), 533–546.
- Capparelli, M.V., Gusso-Choueri, P.K., Abessa, D.M.D.S., McNamara, J.C., 2019. Seasonal environmental parameters influence biochemical responses of the fiddler crab *Minuca rapax* to contamination *in situ*. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 216, 93–100. <https://doi.org/10.1016/j.cbpc.2018.11.012>.
- Carreras-Colom, E., Cartes, J.E., Rodríguez-Romeu, O., Padrós, F., Solé, M., Grelaud, M., Ziveri, P., Palet, C., Soler-Membrives, A., Carrasón, M., 2022. Anthropogenic pollutants in *Nephrops norvegicus* (Linnaeus, 1758) from the NW Mediterranean Sea: uptake assessment and potential impact on health. *Environ. Pollut.* 314, art. no. 120230 <https://doi.org/10.1016/j.envpol.2022.120230>.
- Cenov, A., Perić, L., Glad, M., Žurga, P., Lušić, D.V., Traven, L., Linšak, D.T., Linšak, Ž., Devescovi, M., Bihari, N., 2018. A baseline study of the metallothioneins content in digestive gland of the Norway lobster *Nephrops norvegicus* from northern Adriatic Sea: body size, season, gender and metal specific variability. *Mar. Pollut. Bull.* 131, 95–105. <https://doi.org/10.1016/j.marpolbul.2018.03.002>.
- Chakraborty, S., Ray, M., Ray, S., 2013. Cell to organ: physiological, immunotoxic and oxidative stress responses of *Lamellidens marginalis* to inorganic arsenite. *Ecotox. Environ. Saf.* 94, 153–163. <https://doi.org/10.1016/j.ecoenv.2013.04.012>.
- Chen, L., Lam, J.C.W., Zhang, X., Pan, K., Guo, C., Lam, P.K.S., Wang, W., Liu, H., Qian, P.-Y., 2015. Relationship between metal and polybrominated diphenyl ether (PBDE) body burden and health risks in the barnacle *Balanus Amphitrite*. *Mar. Pollut. Bull.* 100 (1), 383–392. <https://doi.org/10.1016/j.marpolbul.2015.08.020>.
- Covelli, S., Emili, A., Acquavita, A., Koron, N., Faganelli, J., 2011. Benthic biogeochemical cycling of mercury in two contaminated northern Adriatic coastal lagoons. *Cont. Shelf Res.* 31 (16), 1777–1789. <https://doi.org/10.1016/j.csr.2011.08.005>.
- Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.-P., Iglesias, A., Lange, M.A., Lionello, P., Llasat, M.C., Paz, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M.N., Xoplaki, E., 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. *Nat. Clim. Chang.* 8 (11), 972–980. <https://doi.org/10.1038/s41558-018-0299-2>.
- Cresson, P., Fabri, M.C., Bouchouha, M., Brach Papa, C., Chavanon, F., Jadaud, A., Knoery, J., Miralles, F., Cossa, D., 2014. Mercury in organisms from the

- northwestern Mediterranean slope: importance of food sources. *Sci. Total Environ.* 497–498, 229–238. <https://doi.org/10.1016/j.scitotenv.2014.07.069>.
- Cukrov, N., Francisković-Bilinski, S., Hlača, B., Barišić, D., 2011. A recent history of metal accumulation in the sediments of Rijeka harbor, Adriatic Sea. *Croatia. Mar. Pollut. Bull.* 62 (1), 154–167. <https://doi.org/10.1016/j.marpolbul.2010.08.020>.
- Cukrov, N., Francisković-Bilinski, S., Bogner, D., 2014. Metal contamination recorded in the sediment of the semi-closed Bakar Bay (Croatia). *Environ. Geochem. Health* 36 (2), 195–208. <https://doi.org/10.1007/s10653-013-9558-3>.
- Delgado-Suarez, I., Lozano-Bilbao, E., Hardisson, A., Paz, S., Gutiérrez, Á.J., 2023. Metal and trace element concentrations in cetaceans worldwide: a review. *Mar. Pollut. Bull.* 192, art. no. 115010 <https://doi.org/10.1016/j.marpolbul.2023.115010>.
- Dellali, M., Douggui, A., Harrath, A.H., Mansour, L., Alwasel, S., Beyrem, H., Gyedu-Ababio, T., Rohal-Lupher, M., Boufahja, F., 2021. Acute toxicity and biomarker responses in *Gammarus locusta* amphipods exposed to copper, cadmium, and the organochlorine insecticide dieldrin. *Environ. Sci. Pollut. Res.* 28 (27), 36523–36534. <https://doi.org/10.1007/s11356-021-13158-4>.
- Di Lena, G., Casini, I., Caproni, R., Orban, E., 2018. Total mercury levels in crustacean species from Italian fishery. *Food Addit. Contam. B* 11 (3), 175–182. <https://doi.org/10.1080/19393210.2018.1450302>.
- EC 2006. COMMISSION REGULATION (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs.
- Erasmus, J.H., Smit, N.J., Gerber, R., Schaeffner, B.C., Nkabi, N., Wepener, V., 2022. Total mercury concentrations in sharks, skates and rays along the South African coast. *Mar. Pollut. Bull.* 184, art. no. 114142. <https://doi.org/10.1016/j.marpolbul.2022.114142>.
- Fafandel, M., Piljagić, J., Tanković, M.S., Travizi, A., Bihari, N., 2015. Nutrients vs toxicity in sediments: a case study of two semi-closed basins in Rijeka bay. *Croatia. Fresenius Environ. Bull.* 24 (9A), 2888–2897.
- Fitzgerald, W.F., Lamborg, C.H., Hammerschmidt, C.R., 2007. Marine biogeochemical cycling of mercury. *Chem. Rev.* 107 (2), 641–662. <https://doi.org/10.1021/cr050353m>.
- Frasco, M.F., Colletier, J.-P., Weik, M., Carvalho, F., Guilhermino, L., Stojan, J., Fournier, D., 2007. Mechanisms of cholinesterase inhibition by inorganic mercury. *FEBS J.* 274 (7), 1849–1861. <https://doi.org/10.1111/j.1742-4658.2007.05732.x>.
- Freitas, R., Coppola, F., De Marchi, L., Codella, V., Pretti, C., Chiellini, F., Morelli, A., Polese, G., Soares, A.M.V.M., Figueira, E., 2018. The influence of arsenic on the toxicity of carbon nanoparticles in bivalves. *J. Hazard. Mater.* 358, 484–493. <https://doi.org/10.1016/j.jhazmat.2018.05.056>.
- Frías-Espéricueta, M.G., Bautista-Covarrubias, J.C., Osuna-Martínez, C.C., Delgado-Alvarez, C., Bojórquez, C., Aguilar-Juárez, M., Roos-Muñoz, S., Osuna-López, I., Páez-Osuna, F., 2022. Metals and oxidative stress in aquatic decapod crustaceans: a review with special reference to shrimp and crabs. *Aquat. Toxicol.* 242, 106024 <https://doi.org/10.1016/j.aquatox.2021.106024>.
- Govind, C.K., 1992. Age-related remodelling of lobster neuromuscular terminals. *Exp. Gerontol.* 27 (1), 63–74. [https://doi.org/10.1016/0531-5565\(92\)90029-Y](https://doi.org/10.1016/0531-5565(92)90029-Y).
- Gunderson, M.P., Nguyen, B.T., Cervantes Reyes, J.C., Holden, L.L., French, J.M.T., Smith, B.D., Lineberger, C., 2018. Response of phase I and II detoxification enzymes, glutathione, metallothionein and acetylcholine esterase to mercury and dimethoate in signal crayfish (*Pacifastacus leniusculus*). *Chemosphere* 208, 749–756. <https://doi.org/10.1016/j.chemosphere.2018.05.183>.
- Harayashiki, C.A.Y., Reichelt-Brushett, A.J., Liu, L., Butcher, P., 2016. Behavioural and biochemical alterations in *Penaeus monodon* post-larvae diet-exposed to inorganic mercury. *Chemosphere* 164, 241–247. <https://doi.org/10.1016/j.chemosphere.2016.08.085>.
- Harayashiki, C.A.Y., Reichelt-Brushett, A., Butcher, P., Benkendorff, K., 2018. Ingestion of inorganic mercury by juvenile black tiger prawns (*Penaeus monodon*) alters biochemical markers. *Ecotoxicology* 27 (9), 1225–1236. <https://doi.org/10.1007/s10646-018-1975-8>.
- Hermaniuk, A., Van De Pol, L.L.E., Verberk, W.C.E.P., 2021. Are acute and acclimated thermal effects on metabolic rate modulated by cell size? A comparison between diploid and triploid zebrafish larvae. *J. Exp. Biol.* 224 (1), art. no. jeb227124 <https://doi.org/10.1242/jeb.227124>.
- Iamiceli, A., Ubaldi, A., Lucchetti, D., Brambilla, G., Abate, V., De Felip, E., De Filippis, S. P., Dellatte, E., De Luca, S., Ferri, F., Fochi, I., Fulgenzi, A., Iacovella, N., Moret, I., Piazza, R., Roncarati, A., Melotti, P., Fanelli, R., Fattore, E., di Domenico, A., Miniero, R., 2015. Metals in Mediterranean aquatic species. *Mar. Pollut. Bull.* 94 (1–2), 278–283. <https://doi.org/10.1016/j.marpolbul.2015.02.034>.
- Johnson, M.P., Lordan, C., Power, A.M., 2013. Habitat and ecology of *Nephrops norvegicus*. *Adv. Mar. Biol.* 64, 27–63. <https://doi.org/10.1016/B978-0-12-410466-2.00002-9>.
- Joyce, H., Nash, R., Frias, J., White, J., Cau, A., Carreras-Colom, E., Kavanagh, F., 2023. Monitoring microplastic pollution: the potential and limitations of *Nephrops norvegicus*. *Ecol. Indic.* 154, art. no. 110441 <https://doi.org/10.1016/j.ecolind.2023.110441>.
- Juhel, G., Bayen, S., Goh, C., Lee, W.K., Kelly, B.C., 2017. Use of a suite of biomarkers to assess the effects of carbamazepine, bisphenol a, atrazine, and their mixtures on green mussels, *Perna viridis*. *Environ. Toxicol. Chem.* 36 (2), 429–441. <https://doi.org/10.1002/etc.3556>.
- Klarić, S., Pavičić-Hamer, D., Lucu, Č., 2004. Seasonal variations of arsenic in mussels *Mytilus galloprovincialis*. *Helgolönd Mar. Res.* 58 (3), 216–220. <https://doi.org/10.1007/s10152-004-0188-0>.
- Komar, D., Dolenc, M., Dolenc, T., Vrhovnik, P., Lojen, S., Kniewald, G., Matešić, S.S., Lambaša Belak, Z., Orlando-Bonaca, M., 2018. Benthic organisms as ecological indicators for the status assessment of coastal ecosystems. *J. Mar. Biol. Assoc. U.K.* 98 (8), 1907–1917. <https://doi.org/10.1017/S0025315417001527>.
- Kotnik, J., Horvat, M., Ogrinc, N., Fajon, V., Žagar, D., Cossa, D., Sprovieri, F., Pirrone, N., 2015. Mercury speciation in the Adriatic Sea. *Mar. Pollut. Bull.* 96 (1–2), 136–148. <https://doi.org/10.1016/j.marpolbul.2015.05.037>.
- Lagadic, L., 2002. Biomarkers: useful tools for the monitoring of aquatic environments. *Rev. Med. Veterinaire* 153, 581e588.
- Lee, D.-H., Eom, H.-J., Kim, M., Jung, J.-H., Rhee, J.-S., 2017. Non-target effects of antifouling agents on mortality, hatching success, and acetylcholinesterase activity in the brine shrimp *Artemia salina*. *Toxicol. Environ. Health Sci.* 9 (3), 237–243. <https://doi.org/10.1007/s13530-017-0326-0>.
- Lourenço, H.M., Anacleto, P., Afonso, C., Martins, M.F., Carvalho, M.L., Lino, A.R., Nunes, M.L., 2009. Chemical characterisation of *Nephrops norvegicus* from Portuguese coast. *J. Sci. Food Agric.* 89 (15), 2572–2580. <https://doi.org/10.1002/jsfa.3754>.
- MacLeod, C.K., Eriksen, R.S., Chase, Z., Apitz, S.E., 2016. Chemical Pollutants in the Marine Environment: Causes, Effects, and challenges', in Martin Solan, and Nia Whiteley (Eds), Stressors in the Marine Environment: Physiological and Ecological Responses; Societal Implications. <https://doi.org/10.1093/acprof:oso/9780198718826.003.0013>.
- Marković, O., Ikića, Z., Đurović, M., Mandić, M., Pešić, A., Petović, S., Joksimović, A., 2016. Some preliminary data about reproductive activity of female of *Nephrops norvegicus* (Linnaeus, 1758), in the South Adriatic Sea (Montenegro). *Turk. J. Fish. Aquat.* 16 (3), 8. https://doi.org/10.4194/1303-2712-v16_3_29.
- Maulvault, A.L., Camacho, C., Barbosa, V., Alves, R., Anacleto, P., Cunha, S.C., Fernandes, J.O., Pousão-Ferreira, P., Paula, J.R., Rosa, R., Diniz, M., Marques, A., 2019. Bioaccumulation and ecotoxicological responses of juvenile white seabream (*Diplodus sargus*) exposed to triclosan, warming and acidification. *Environ Poll* 245, 427–442. <https://doi.org/10.1016/j.envpol.2018.11.020>.
- Mesquita, S.R., Guilhermino, L., Guimarães, L., 2011. Biochemical and locomotor responses of *Carcinus maenas* exposed to the serotonin reuptake inhibitor fluoxetine. *Chemosphere* 85 (6), 967–976. <https://doi.org/10.1016/j.chemosphere.2011.06.067>.
- Miettinen, T.P., Caldez, M.J., Kaldis, P., Björklund, M., 2017. Cell size control – a mechanism for maintaining fitness and function. *BioEssays* 39 (9), art. no. 1700058. <https://doi.org/10.1002/bies.201700058>.
- Mille, T., Cresson, P., Chouvelon, T., Bustamante, P., Brach-Papa, C., Sandrine, B., Rozuel, E., Bouchoucha, M., 2018. Trace metal concentrations in the muscle of seven marine species: comparison between the Gulf of lions (north-West Mediterranean Sea) and the Bay of Biscay (north-East Atlantic Ocean). *Mar. Pollut. Bull.* 135, 9–16. <https://doi.org/10.1016/j.marpolbul.2018.05.051>.
- Moleiro, P., Morais, T., Leite, C., Coppola, F., Henriques, B., Pinto, J., Soares, A.M.V.M., Pereira, E., Freitas, R., 2022. The effect of ocean warming on accumulation and cellular responsiveness to cobalt in *Mytilus galloprovincialis*. *Mar. Pollut. Bull.* 182, art. no. 113944 <https://doi.org/10.1016/j.marpolbul.2022.113944>.
- Moncaleano-Niño, A.M., Luna-Acosta, A., Gómez-Cubillos, M.C., Villamil, L., Ahrens, M. J., 2018. Cholinesterase activity in the cup oyster *Saccostrea sp.* exposed to chlorpyrifos, imidacloprid, cadmium and copper. *Ecotox. Environ. Saf.* 151, 242–254. <https://doi.org/10.1016/j.ecoenv.2017.12.057>.
- Oliva, M., De Marchi, L., Cuccaro, A., Casu, V., Tardelli, F., Monni, G., Freitas, R., Caliani, I., Fossi, M.C., Fratini, S., Baratti, M., Pretti, C., 2019. Effects of copper on larvae of the marbled crab *Pachygrapsus marmoratus* (Decapoda, Grapsidae): toxicity test and biochemical marker responses. *Comp. Biochem. Phys. C* 223, 71–77. <https://doi.org/10.1016/j.cbpc.2019.05.007>.
- Oliveira, C., Almeida, J.R., Guilhermino, L., Soares, A.M.V.M., Gravato, C., 2013. Swimming velocity, avoidance behavior and biomarkers in *Palaeomon serratus* exposed to fenitrothion. *Chemosphere* 90 (3), 936–944. <https://doi.org/10.1016/j.chemosphere.2012.06.036>.
- Orsi Relini, L., Zamboni, A., Fiorentino, F., Massi, D., 1998. Reproductive patterns in Norway lobster *Nephrops norvegicus* (L.), (Crustacea Decapoda Nephropidae) of different Mediterranean areas. *Sci. Mar.* 62 (SUPPL.1), 25–41.
- Pereira, B.V.R., Silva-Zacarin, E.C.M., Costa, M.J., Dos Santos, A.C.A., do Carmo, J.B., Nunes, B., 2019. Cholinesterases characterization of three tropical fish species, and their sensitivity towards specific contaminants. *Ecotox. Environ. Saf.* 173, 482–493. <https://doi.org/10.1016/j.ecoenv.2019.01.105>.
- Perić, L., Burić, P., 2019. The effect of copper and chlorpyrifos co-exposure on biomarkers in the marine mussel *Mytilus galloprovincialis*. *Chemosphere* 225, 126–134. <https://doi.org/10.1016/j.chemosphere.2019.03.003>.
- Perić, L., Petrović, S., 2011. Acetylcholinesterase activity in the gills of mussels (*Mytilus galloprovincialis*) from the north-eastern Adriatic coast. *Fresen. Environ. Bull.* 20 (11), 2855–2860.
- Perić, L., Fafandel, M., Glad, M., Bihari, N., 2012. Heavy metals concentration and metallothionein content in resident and caged mussels *Mytilus galloprovincialis* from Rijeka Bay, Croatia. *Fresen. Environ. Bull.* 21 (9 A), 2785–2794.
- Perugini, M., Visciano, P., Manera, M., Zaccaroni, A., Olivieri, V., Amorena, M., 2009. Levels of total mercury in marine organisms from Adriatic Sea. *Italy. Bull. Environ. Contam. Toxicol.* 83 (2), 244–248. <https://doi.org/10.1007/s00128-009-9758-9>.
- Perugini, M., Visciano, P., Manera, M., Abete, M.C., Tarasco, R., Amorena, M., 2014. Lead, cadmium and chromium in raw and boiled portions of Norway lobster. *Food Addit. Contam. B* 7 (4), 267–272. <https://doi.org/10.1080/19393210.2014.91866>.
- Qian, Y., Zhang, W., Yu, L., Feng, H., 2015. Metal pollution in coastal sediments. *Curr. Pollut. Rep.* 1 (4), 203–219. <https://doi.org/10.1007/s40726-015-0018-9>.
- Ramos, A.S., Antunes, S.C., Nunes, B., 2016. Biomonitoring of environmental stress in *Pollicipes pollicipes* from the northern coast of Portugal: a non-destructive approach using haemolymph. *Ecotox. Environ. Saf.* 126, 1–13. <https://doi.org/10.1016/j.ecoenv.2015.12.008>.
- Rodrigues, A.P., Olivae Teles, T., Mesquita, S.R., Delerue Matos, C., Guimarães, L., 2014. Integrated biomarker responses of an estuarine invertebrate to high abiotic

- stress and decreased metal contamination. *Mar. Environ. Res.* 101 (1), 101–114. <https://doi.org/10.1016/j.marenvres.2014.10.001>.
- RStudio Team, 2017. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA (URL <http://www.rstudio.com/>).
- Santos, G.P.C.D., Assis, C.R.D.D., Oliveira, V.M., Cahu, T.B., Silva, V.L., Santos, J.F., Yogui, G.T., Bezerra, R.S., 2022. Acetylcholinesterase from the charru mussel *Mytella charruana*: kinetic characterization, physicochemical properties and potential as in vitro biomarker in environmental monitoring of mollusk extraction areas. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 252, 109225 <https://doi.org/10.1016/j.cbpc.2021.109225>.
- Sardá, F., 1995. A review (1967–1990) of some aspects of the life history of *Nephrops norvegicus*. *ICES Marine Science Symposium* 199, 78–88.
- Sekulić, B., Sapunar, J., Bažulić, D., 1993. Arsenic in Norway lobster (*Nephrops norvegicus* L.) from Kvarnerić Bay-northeastern Adriatic. *Bull. Environ. Contam. Toxicol.* 51 (3), 460–463. <https://doi.org/10.1007/BF00201767>.
- Silva, C.O., Novais, S.C., Alves, L.M.F., Soares, A.M.V.M., Barata, C., Lemos, M.F.L., 2019. Linking cholinesterase inhibition with behavioural changes in the sea snail *Gibbula umbilicalis*: effects of the organophosphate pesticide chlorpyrifos. *Comp. Biochem. Phys. C* 225, art. no. 108570 <https://doi.org/10.1016/j.cbpc.2019.108570>.
- Solé, M., de la Parra, L.M.G., Alejandre-Grimaldo, S., Sardá, F., 2006. Esterase activities and lipid peroxidation levels in offshore commercial species of the NW Mediterranean Sea. *Mar. Pollut. Bull.* 52 (12), 1708–1716. <https://doi.org/10.1016/j.marpolbul.2006.07.015>.
- Stenton, C.A., Bolger, E.L., Michenot, M., Dodd, J.A., Wale, M.A., Briers, R.A., Hartl, M.G. J., Diele, K., 2022. Effects of pile driving sound playbacks and cadmium co-exposure on the early life stage development of the Norway lobster, *Nephrops norvegicus*. *Mar. Pollut. Bull.* 179, art. no. 113667 <https://doi.org/10.1016/j.marpolbul.2022.113667>.
- Storelli, M.M., Marcotrigiano, G.O., 2001. Total, organic, and inorganic arsenic in some commercial species of crustaceans from the Mediterranean Sea (Italy). *J. Food Prot.* 64 (11), 1858–1862. <https://doi.org/10.4315/0362-028X-64.11.1858>.
- Taylor, L.J., Mann, N.S., Daoud, D., Clark, K.F., van den Heuvel, M.R., Greenwood, S.J., 2019. Effects of sublethal Chlorpyrifos exposure on Postlarval American lobster (*Homarus americanus*). *Environ. Toxicol. Chem.* 38 (6), 1294–1301. <https://doi.org/10.1002/etc.4422>.
- Triassi, M., Nardone, A., Giovinetti, M.C., De Rosa, E., Canzanella, S., Sarnacchiaro, P., Montuori, P., 2019. Ecological risk and estimates of organophosphate pesticides loads into the Central Mediterranean Sea from Volturno River, the river of the “land of fires” area, southern Italy. *Sci. Total Environ.* 678, 741–754. <https://doi.org/10.1016/j.scitotenv.2019.04.202>.
- Tursi, A., Maiorano, P., Sion, L., et al., 2015. Fishery resources: between ecology and economy. *Rend. Fis. Acc. Lincei* 26, 73–79. <https://doi.org/10.1007/s12210-014-0372-3>.
- Uluturhan, E., Darilmaz, E., Kontas, A., Bilgin, M., Alyuruk, H., Altay, O., Sevgi, S., 2019. Seasonal variations of multi-biomarker responses to metals and pesticides pollution in *M. Galloprovincialis* and *T. Decussatus* from Homa lagoon. Eastern Aegean Sea. *Mar. Pollut. Bull.* 141, 176–186. <https://doi.org/10.1016/j.marpolbul.2019.02.035>.
- van Oosterom, J., Codi King, S., Negri, A., Humphrey, C., Mondon, J., 2010. Investigation of the mud crab (*Scylla serrata*) as a potential bio-monitoring species for tropical coastal marine environments of Australia. *Mar. Pollut. Bull.* 60 (2), 283–290. <https://doi.org/10.1016/j.marpolbul.2009.09.007>.
- Vázquez-Boucard, C., Anguiano-Vega, G., Mercier, L., Del Castillo, E.R., 2014. Pesticide residues, heavy metals, and DNA damage in sentinel oysters *Crassostrea gigas* from Sinaloa and Sonora. Mexico. *J. Toxicol. Environ. Heal. A* 77 (4), 169–176. <https://doi.org/10.1080/15287394.2013.853223>.
- Ventura-Lima, J., Bogo, M.R., Monserrat, J.M., 2011. Arsenic toxicity in mammals and aquatic animals: a comparative biochemical approach. *Ecotox. Environ. Saf.* 74 (3), 211–218. <https://doi.org/10.1016/j.ecoenv.2010.11.002>.
- Visciano, P., Perugini, M., Manera, M., Abete, M.C., Tarasco, R., Salese, C., Amorena, M., 2013. Total arsenic in raw and boiled portions of Norway lobster (*Nephrops norvegicus*) from the Central Adriatic Sea. *J. Agric. Food Chem.* 61 (50), 12445–12449. <https://doi.org/10.1021/jf404221y>.
- Wiech, M., Dønne, C., Kolding, J., Kjelleve, M., Ferter, K., 2021. Targeted risk assessment of mercury exposure of recreational fishers: are nephrops fishers in Norway at risk? *Environ. Sci. Pollut. Res.* 28 (36), 50316–50328. <https://doi.org/10.1007/s11356-021-14093-0>.
- Yologlu, E., Ozmen, M., 2015. Low concentrations of metal mixture exposures have adverse effects on selected biomarkers of *Xenopus laevis* tadpoles. *Aquat. Toxicol.* 168, 19–27. <https://doi.org/10.1016/j.aquatox.2015.09.006>.
- Zacchetti, L., Martinelli, M., Colella, S., Santojanni, A., Fanelli, E., 2022. Seasonal variations in the feeding ecology of *Nephrops norvegicus* in the Adriatic Sea: insights from stomach contents and stable isotope analyses. *Mar. Ecol. Prog. Ser.* 695, 109–123. <https://doi.org/10.3354/meps14119>.