CHALLENGES TO MARINE ECOSYSTEMS

Catch me in winter! Seasonal variation in air temperature severely enhances physiological stress and mortality of species subjected to sorting operations and discarded during annual fishing activities

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Abstract Several studies have considered the direct and indirect effects of demersal trawling on discarded species in terms of sublethal damages, survival, and stress due to the fishing processes. Nevertheless the effects of air temperature on the physiological stress and the survival of species during sorting operations were only marginally explored. This factor could be particularly important in the context of sustainable fisheries at temperate latitudes where the seasonal variation of air temperature can be particularly pronounced. In this study the seasonal effects of rapido trawling on the non-target species *Liocarcinus depurator* (Portunidae) in the Northern Adriatic Sea (Mediterranean Sea) have been compared by applying survival tests and considering the unbalance in metabolites' concentration as indicators of physiological stress. Results showed consistently higher mortalities during exposure to air in summer (temperature: 28°C), which reached about 96% in 20 min, compared to winter (temperature: 9°C) when only 2% of individuals died. Furthermore trawled and emersed crabs showed significant increase of hemolymph ammonia, lactate, and glucose concentrations as effects of extreme exercise and suffocation, which was more prominent during summer, suggesting that air temperature can play an important role in determining non-target species survival.

Keywords Physiological stress · Mortality · Fishing disturbance · Discard · *Liocarcinus depurator* · Northern Adriatic Sea

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Introduction

Fishing activity constitutes one of the major sources of ecological disturbance (sensu White & Pickett, 1985) and alteration among human exploitation of the marine ecosystems (Williams, 1998). The effects of intense and lasting fishing have been widely investigated to assess the possible effects on marine resources and biodiversity (Jennings & Kaiser, 1998) and to delineate effective guidelines for sustainable fisheries (Pikitch et al., 2005). The overexploitation of marine resources has been recognized to cause drastic impairments of the food web structure and the

consequent alteration of the productivity (Pauly & Christensen, 1995). Besides, fishing has dramatic effects on the non-target species, and the different techniques employed have been proved to cause a wide range of alterations to biodiversity and community structure (Jennings et al., 2001; Queirós et al., 2006; Tillin et al., 2006). These aspects are reflected, for example, by the pronounced imbalance in terms of damage, physiological stress, and survival among the species subjected to trawling activities. In fact during the fishing process, which includes not only capture by the fishing gear, but also the exposure on deck during commercial catch sorting operations, the individuals may suffer physical damage (Bergmann et al., 2001a; Pranovi et al., 2001) and physiological stress due to thermal shocks and exposure to air (Bergmann et al., 2001b; Gamito & Cabral, 2003) which can lead to high mortality rates (Kaiser & Spencer, 1995; Bergmann & Moore, 2001). Among the discarded species, crustaceans constitute a prominent part of the total biomass and represent an excellent candidate to assess the physical and physiological effects of trawling and sorting procedures (Bergmann et al., 2001b; Pranovi et al., 2001). In particular, emersion represents, for sublittoral species, a traumatic event that induces increased physiological disruption (Burnett, 1988; Durand & Regnault, 1998). The permanence in the emersed state causes a collapse of the gas-exchange organs like the lamellate and the filamentous gills (McMahon, 2001). The exchanges, normally occurring at the level of these organs, are reduced or blocked leading to an increase of concentration of respiratory and metabolic end products in the hemolymph and tissues. The suffocation in air is, in fact, connected with the rapid increase in hemolymph CO_2. This effect, together with pronounced lactate accumulation derived from the anaerobic metabolism, causes the marked respiratory acidosis. As for the gas exchange, during emersion the excretion across gills is reduced leading to an increase of ammonia concentrations in the hemolymph and tissues (Danford et al., 2002). Moreover, the trawling and the emersion events stimulate mechanical exercise and stress for the discarded animals, and these are reflected in a pronounced hyperglycemia caused by the increased glycogen utilization (Taylor & Spicer, 1987; Hagerman et al., 1990; Schmitt & Uglow, 1997). These indicators have been applied to the study of the

physiological effects of fishing disturbance on discarded species and, recently, to *Liocarcinus depurator* (Portunidae) in the Clyde Sea (Bergmann et al., 2001b). *L. depurator* is a species distributed in the sublittoral areas from the Mediterranean to the North Sea, and is frequently caught and discarded by demersal fishery all over the continental shelves. *L. depurator* represents a major component of the discard in the Northern Adriatic Sea fishing industry and is usually subjected to high levels of lethal and sublethal injuries during trawling (Pranovi et al., 2001). Some recent papers highlighted the role of air temperature on the survival of crustaceans during the fishing process (Cabral et al., 2002; Gamito & Cabral, 2003).

The aim of this study is to explore the effect of seasonality, reflected by differences of water and air temperatures, as a source of mortality and physiological impairment in individuals of *L. depurator* discarded by commercial trawl fishing activity in the Northern Adriatic Sea. Accordingly, the mortality rate and the physiological disruption have been analyzed and compared during winter and summer trawls and after the subsequent exposure in air, at temperatures of 9°C and 28°C, respectively.

Materials and methods

Experimental trawls and animal sampling

During March 2002 and July 2003 a total number of 8 experimental rapido tows (for fishing gear description see Hall-Spencer et al., 1999) were carried out in the Northern Adriatic Sea (latitude: 45° 03′ N, longitude: 13° 01′ E; depth: 27 m), using a commercial fishing vessel belonging to the port of Chioggia. To reproduce the fishing procedures and to standardize the experimental setting, each tow lasted 40 min at a full speed of 11 km h^{-1}. During the winter experiment, the seabed temperature was 9°C and the air temperature varied between 9 and 12°C; during the summer experiment, the seabed temperature was 14°C, and the air temperature varied between 26 and 28°C. Intermolt adult specimens of *Liocarcinus depurator* were randomly collected from the discard and immediately employed for the survival experiment or for the physiological stress analyses. The designations of molt stage were according to those described by Mangum (1985).

Survival tests

The mortality rates of *L. depurator* were assessed on 100 individuals per tow (3 replicates) immediately after the net was emptied on deck, and after 10 and 20 min of air exposure. In conformity with Bergmann & Moore (2001), individuals were deemed to be dead when no movement of scaphognatite and reaction to external stimulus were observed.

Physiological stress assessment

The physiological stress evaluation was carried out at two different stages of the fishing process: immediately after the end of the tow and during the sorting process. In the first group (hereafter referred to as "trawled"), individuals were immediately collected from the catch (within 3 min) and put into tanks filled with sea water at the same temperature as the seabed water; hemolymph samples were withdrawn within 5 to 15 min of the end of each tow. The second group consisted of individuals (hereafter referred to as "trawled and emersed") which were left on deck exposed to air. Hemolymph samples were withdrawn continuously from randomly selected individuals: 5 to 45 min (winter experiment) and 5 to 25 min (summer), respectively, after the end of the tow. Hemolymph was withdrawn just once from each animal. During the same cruise, to test undisturbed individuals, not subjected to the catch stress induced by the trawl, baited creels were used and six specimens were collected and used as control group. During the summer experiment the same procedures were applied to the trawled group, but, due to the high mortality rate of the emersed crabs, the air exposure was shortened to 5 min.

Hemolymph sampling and analysis

Hemolymph was collected from individuals using a 1 ml syringe whose needle was inserted into the pericardium from the posterior side of the carapace to reduce the duration of handling and to collect post-branchial blood. The samples were immediately frozen and kept in liquid nitrogen until arrival in the lab where they were stored at $-20°C$ until used. Each hemolymph sample was generally used for the determination of all metabolites, but when the sample volume was too small, lactate and glucose measurements were preferred because they need less material to be assessed. The number of individuals sampled for each assay ranged between 23–41 as indicated in Fig. 2.

The concentration of total NH_3/NH_4^+ nitrogen was determined colorimetrically using the method described by Solorzano (1969) with an absorbance reading at 634 nm. Concentration values were determined by reference to a calibration plot obtained by suitable dilutions of a 1 mM NH_4Cl solution. The calibration plot was established in a concentration range so as to include the concentration in the experimental specimens.

L-lactate concentration was determined according to the method of Gutmann & Wahlefeld (1974) based on the substrate oxidation to L-pyruvate catalyzed by lactate dehydrogenase in an assay medium made with 3.75 g/100 ml glycine, 2.0 ml/100 ml hydrazine hydrate (96%) buffered to pH 9.0 with NaOH and containing 6 mM EDTA to remove the interferences due to divalent cations in solution (Engel & Jones, 1978). NAD^+ 40 mM and lactate dehydrogenase (510 U/mg diluted 1:2 in buffer) were also used.

The quantitative assay for D-glucose concentration is based on the hexokinase-catalyzed phosphorylation of the substrate (ATP is required as co-substrate) followed by the one-electron oxidation of glucose-6-phosphate by the dehydrogenase that produces NADPH (Webster, 1996). The assay is carried out in 0.1 M Tris/HCl pH 7.4 containing 5 mM $MgSO_4$. Both L-lactate and D-glucose assays were carried out with the internal standard method.

The concentration of the assayed compounds was calculated after extrapolating to zero the internal standard concentration and correction for dilutions. All spectrophotometric determinations were carried out with a Hewlett-Packard HP-8452 diode array spectrophotometer and all the reagents employed for the analyses were purchased from Sigma-Aldrich.

Statistical analysis

The mean value of the metabolic parameter was pairwise compared by Mann–Whitney U-test. The analyses were applied between the summer and winter trawled samples, and the summer and winter trawled and emersed samples. Due to the low number of specimens collected, the control group was not included in the analyses but presented in the figures

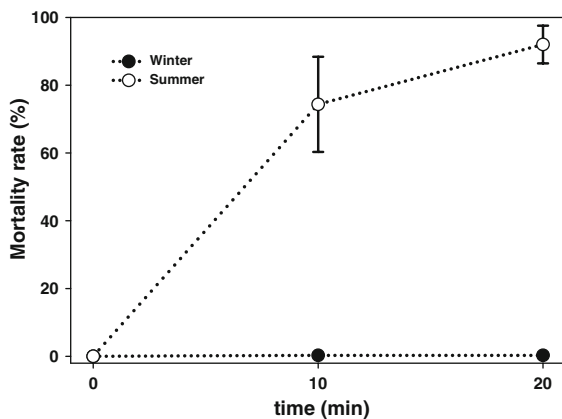simply as references. The limit of significance was considered at $P < 0.001$.

Results

Survival tests

The short-term analyses of mortality rates highlighted the presence of a strong seasonal effect, since during the winter experiment, less than 2% of collected individuals died within 20 min of exposure to air, whereas during the summer experiments up to 96% died in the same time (Fig. 1).
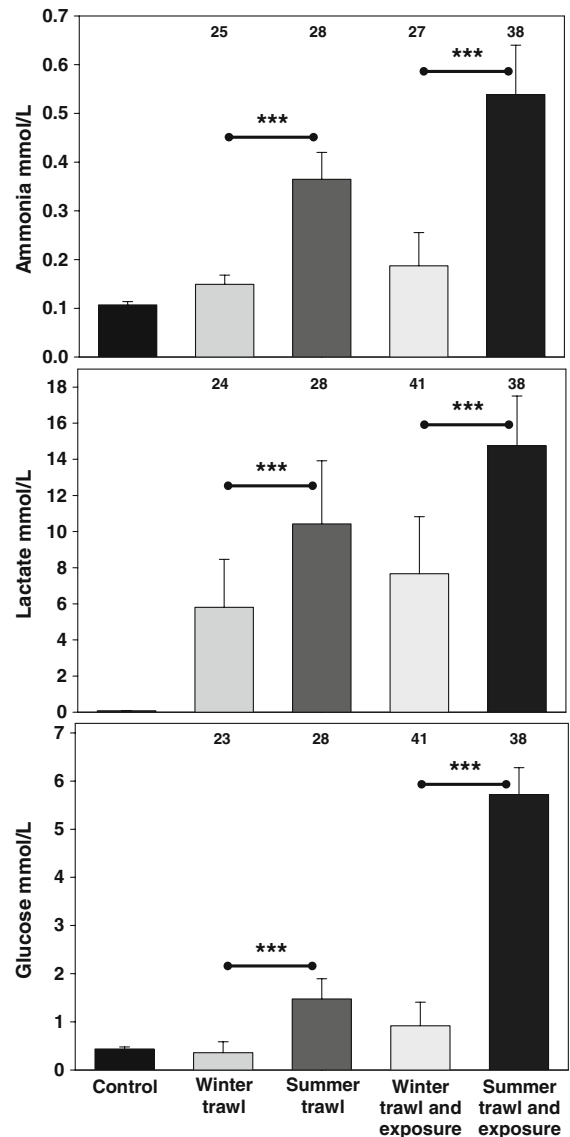
Physiological stress estimation

The alteration of physiological state due to the stress condition occurring during the trawling or/and air exposure can be studied by measuring the concentration levels in the hemolymph of ammonia, L-lactate, D-glucose. In Fig. 2 are shown the data obtained in "trawled" and "trawled and emersed" groups of animals. The creel-caught individuals are used as a control group for comparison with the other conditions, but only as a reference because of the reduced number of specimens. The "reference" data are the average of both the winter and summer values.

The animals collected by rapido trawling in winter showed average ammonia levels of 0.149 ± 0.019 mmol l^{-1}, slightly higher than the value registered in the control group (0.107 ± 0.007 mmol l^{-1}), but in summer the concentration in the hemolymph increased

Fig. 2 Hemolymph ammonia, lactate, and glucose concentrations (mmol $l^{-1} \pm$ s.d.) measured on experimental crabs. The bars represent the value of concentrations for only trawled and trawled and emersed specimens both in summer and winter catches. The numbers over the bars represent the number of specimens considered while the control group was constantly constituted by six animals. The horizontal bars indicate the pairwise comparisons and the *** stand for the significance values ($P < 0.001$)

up to 0.365 ± 0.055 mmol l^{-1}. In the group of individuals subjected to emersion after trawling, the ammonia value increased with respect to the non-exposed group, both in winter and summer, reaching values of 0.187 ± 0.068 mmol l^{-1} and 0.539 ± 0.101 mmol l^{-1}, respectively.

Fig. 1 Cumulative mortality rates (%) in *Liocarcinus depurator* caught by rapido trawl in summer (○) and winter (●), at the end of the tow (0) and after 10 and 20 min of air exposure

Lactate was considerably low in the control group (0.068 ± 0.010 mmol l^{-1}) indicating a low stress condition in the animals captured by baited creels. As far as the winter experiment is concerned, the lactate concentration was 5.808 ± 2.654 mmol l^{-1} in trawled individuals, but in air-exposed individuals the levels increased to 7.666 ± 3.160 mmol l^{-1}. A drastic lactate concentration increase was observed in summer: the trawled group showed a value of 10.422 ± 3.497 mmol l^{-1}, about twice the corresponding value in winter while the highest level was achieved in exposed individuals at 14.750 ± 2.755 mmol l^{-1}.

The concentration of glucose in hemolymph of control group was 0.435 ± 0.044 mmol l^{-1}. In winter the variation of glucose levels in trawled animals appears restrained (0.359 ± 0.227 mmol l^{-1}) and there was an increase up to 0.918 ± 0.491 mmol l^{-1} in the air-exposed individuals. In summer the glucose levels exhibited remarkable differences as compared to winter experiments: the trawled group showed a value of 1.475 ± 0.420 mmol l^{-1}, about 300% higher than that in winter experiment, but the exposure to air produced a strong increase reaching the concentration of 5.719 ± 0.559 mmol l^{-1}, 6–7 times higher as compared to the corresponding winter group.

Discussion

The effects of air exposure on crustacean physiology have been accurately described in species that normally experience emersion in the intertidal and coastal fringes (e.g. Bridges & Brand, 1981; DeFur, 1988; Taylor & Spicer, 1988; Stillman & Somero, 1996) as well as for subtidal species that could be forced to emersion as a consequence of commercial fishing activities (Schmitt & Uglow, 1997; Morris & Oliver, 1999a, b; Bergmann et al., 2001b; Danford et al., 2002). From this literature, it emerges that during sorting and shipping procedures benthic crustaceans, which inhabit stable environments and are virtually unable to cope with emersion, undergo a series of circulatory, respiratory, and metabolic impairments. These effects generally produce cumulative consequences on organisms and usually lead rapidly to mortalities.

Results obtained in the present study are consistent with previous findings about the physiological tolerance to emersion in *Liocarcinus depurator* (Bergmann et al., 2001b) and reveal the pronounced sensitivity of this species to mechanical stress during trawling action and to emersion during the sorting process. Moreover, they pointed out the extreme importance of the season in determining the disturbance magnitude on discarded species, underlining the role of the temperature effect in the fishing activities at temperate latitudes. In detail, survival tests showed the extent of seasonal influence, reflected in air and water temperature variations, on the survival chances of individuals involved in the fishing process. On the other hand, the physiological analyses provided the description of the metabolic disruption enhanced by higher temperatures during this stressful and unnatural event. During emersion the collapse of the gills produces a sudden breakdown of gas-exchange and excretion processes, with the consequent accumulation, at the level of tissues and hemolymph, of different metabolic end products (DeFur, 1988; Taylor & Whiteley, 1989). The increase of lactate, CO_2, H^+ concentrations normally occurs during the pronounced anaerobiosis together with the progressive accumulation of ammonia, urate, and amine in the hemolymph (Durand & Regnault, 1998; Danford et al., 2002). Besides, fishing procedures like trawling and sorting constitute stressful events both for commercial and discarded species and generally increase animal activities and metabolism which finally produce addictive effects to the homeostasis disruption (Bergman et al., 2001b). The physiological response of sublittoral organisms to air exposure appears to be markedly species specific and the extent of sublethal levels of metabolites like ammonia and lactate shows a wide range. In portunid crabs, experimentally emersed for 18 h, blood ammonia reaches values of 0.12 mmol l^{-1} in the intertidal *Carcinus maenas* and 1.3 mmol l^{-1} in the sublittoral *Necora puber* (Durand & Regnault, 1998). Similarly, *L. depurator* subjected to ca. 40 min of emersion after fishing trawl presents value of 0.308 mmol l^{-1} of blood ammonia (Bergman et al., 2001b). All these values appear to be sublethal for the investigated species, in consideration with the small mortality rate recorded and with the complete recovery during reimmersion in water. Comparable values

of blood ammonia have been measured in the present study both in trawled and trawled and emersed crabs during winter activities, suggesting a sublethal accumulation of nitrogen compounds during emersion. On the contrary, the severe increase of blood ammonia resulting from summer analyses could be a consequence of the accelerated metabolism at the higher temperatures and could partially be responsible for the pronounced mortality rate recorded.

The rapid switch to anaerobic metabolism during emersion produces a high rate of increase in blood lactate level in portunid crabs; however, these species show an efficient mechanism of repayment of the oxygen debt and a rapid restoration of normoxic conditions usually occurs during recovery in water. In particular, when sublittoral species such as *N. puber* are subjected to emersion, individuals show increasing value of blood lactate which reaches 9 mmol l^{-1} and 60 mmol l^{-1} after 4 and 18 h of air exposure, respectively (Durand & Regnault, 1998). *L. depurator* appears to be more sensitive to emersion showing lactate concentrations in hemolymph of 6.2 mmol l^{-1} after 40 min in air following fishing trawling (Bergman et al., 2001b). Similar results are obtained in the present study for the winter samples. In addition, we have observed a prominent effect of the trawl motion rather than the emersion as the cause of stimulation of anaerobic metabolism (compare "trawl" and "trawl and exposure" data of Fig. 2). The mechanical solicitations and the elevated exercise inside the net seem to account for the principal fraction of the total oxygen debt. In summer these effects are significantly enhanced as a consequence of the thermal stress and accelerated metabolism.

In crustaceans, glycogen is the principal reserve of carbohydrates and constitutes the main source of energy during intense and protracted exercise; thus, high levels of circulating glucose represent a reliable indicator of energetic investment (Briffa & Elwood, 2001, 2002). Although glucose concentration could depend on a number of physiological factors and should be carefully adopted as a stress indicator (Kallen et al., 1990; Chang, 1995), the quantification of hemolymph glucose has been used to assess the effect on trawling. Exercise and emersion on *L. depurator*, reveal a significant increase of this metabolite following highly disturbing treatments (Bergman et al., 2001b). Our results agree with the

previous studies, but evidenced also for glucose mobilization remarkable differences as a function of the season. The hemolymph concentration in summer experiments, in fact, reached values 6–7 fold higher than that achieved in winter, underlining the effect of temperature on the metabolic disruption.

The evaporative water loss during the emersion constitutes an important cause of homeostasis disturbance and might partially contribute to increased metabolite concentration in crab hemolymph. However, on the basis of the limited reduction in body wet weight reported for *L. depurator* caught in the Clyde Sea and exposed to air for 1 h (Bergmann et al., 2001b), evaporative water loss is likely to be not the main factor in inducing the sharp metabolites' increase observed during the experiments here reported.

The integration of the survival tests with the physiological evaluation of the stress, occurring during trawling and sorting operations, suggests that a decline of *L. depurator* populations should be expected. This conclusion is further supported by the indication that 24 h are necessary for fully recovering the induced physiological impairment (Bergmann et al., 2001b) and that the occurrence of sublethal damages, such as limb loss, hamper the foraging efficiency and agonistic behavior of crabs (Pranovi et al., 2001; Bergmann et al., 2001a). However, data from surveys show a rather stable situation for the Northern Adriatic Sea (Raicevich, 2004). The hypothesis of a trade-off between energetic costs, associated with the fishing disturbance, and energetic benefits, due to discard supply can be put forward: the scavenging behavior of *L. depurator* (Bergmann et al., 2002) would, indeed, allow populations of this species to exploit the supplementary, low-energy expenditure, source of food given by individuals of other species discarded by fishing activities. A similar hypothesis has been proposed also for the scavenging starfish *Asterias rubens* in the North Sea (Ramsay et al., 2000).

The extension of this study to other species could make it possible to rank the non-target species on the basis of their vulnerability to fishing. Such rank could include physiological aspects based on field observation and mortality assessment, integrating former assessments mainly based on life-history and fragility features (Macdonald et al., 1996). In spite of the different mechanisms responsible for the resilience to

fishing disturbance in populations of scavengers species, studies showing high discard mortality rates should be considered by the authorities to enforce the legislation aimed to reduce this adverse effect of fishing on non-target species. For instance, the summer fishing ban already implemented (1 month) in the Northern Adriatic Sea could be extended to the whole summer season, avoiding discard production in the period when specimens are more likely to suffer high mortality rates and physiological impairment.

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