

Physiological energetics of the brown mussel *Perna perna* (L.) transplanted in the Itajaí-Açu river mouth, Southern Brazil

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Abstract Groups of the mussel *Perna perna* were transplanted to two points and at three different depths in the coastal region close to the Itajaí-Açu River mouth, an impacted river in the south of Brazil. With the objective of evaluating the physiology changes in the organisms in relation to the control area (origin of the organisms), the clearance, respiration and excretion rates, absorption efficiency and growth were estimated. The levels of metals in the organism tissue were determined in an attempt to explain the physiological changes occurring in the study area. Organisms from Point 2 placed near the bottom showed physiological changes in comparison to the control and the transplanted organisms from Point 1. Point 2 showed greater sediment resuspension and availability of trace metals to the organisms closer to the bed. The increase in Cr concentration in the tissues of the organisms (up to $0.21 \text{ mg kg}^{-1} \text{ ww}$) was not sufficient to explain the decrease in the inhibition of clearance (28.8%) and in the absorption efficiency (15.7%), or the increased excretion rate (282.5%), which led to the organisms having a reduced scope for growth (48.6%). This indicates the possible presence of other contaminants, which were not measured, and which probably had synergistic action with the trace metals investigated.

Keywords Metals · Bivalve physiology · Sub-lethal effects · Coast · Pollution effects

Introduction

The determination of ecotoxicological potential is most realistically carried out in situ due to the integration between contaminant effects, between contaminants and natural water constituents, and between biological processes (Clements and Kiffney 1994). In this regard, bioactive monitoring, such as organism transplantation, is fundamental to understanding environmental impacts (Rand 1995). The Itajaí-Açu River basin is subjected to demographic pressure with the presence of 3,000 industrial plants, including textile, metal-mechanical, fishing, meat, paper, and leather, industries, as well as other smaller industries (Pereira Filho et al. 2003). Also, the river basin comprises more than 160 thousand hectares of cultivated land in the rural zone, where the main crops are irrigated rice, corn, tobacco, onion, and banana (Gommersbach 2000). As a result, the Itajaí-Açu River estuary receives all of the sediments and pollutants from the basin, and it is also a densely populated and highly industrially development area. The Port of Itajaí, installed nearly 4 km from the estuary mouth, is the main trade route of the state, as well as being one of the most important ports in Brazil.

It is expected that there is a high quantity of contaminants flowing into the Itajaí River, such as those originated from effluents with high levels of organic matter (BOD_5 , P-PO_4^{3-}) from the fish processing industry and domestic sewage; chrome and zinc from the textile and metal-mechanical industries; and effluents containing halogenated composites (AOX; Rörig 2005). However, the estuary has the capacity to neutralize the majority of contaminants such as N-NH_4^+ , surfactants and total copper in the water, through adsorption and sedimentation processes (Rörig 2005) transferring the organic and metallic contamination to the sediment (Laitano and Resgalla 2000). The fine

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sediment trapping in the estuary is strongly regulated by the river discharge. During periods of low fluvial discharge, most of the fluvial material is retained within the estuary (Schettini et al. 2006). However, during periods of moderate to high fluvial discharge, most of the material is transported directly to the adjacent shelf (Schettini and Toldo 2006), forming a buoyant plume, spreading out from the inlet mainly towards the north-northeast (Schettini et al. 1998; Trochimczuk and Schettini 2003).

The objective of this study was to evaluate the influence of the river plume and the quality of the sediment on the mussel *Perna perna* transplanted to two points in front of the mouth of the Itajaí-Açu estuary, in order to investigate the environmental impact of the levels of river/estuary-borne contaminants to the coastal zone.

Materials and methods

The 'field laboratory' of this study was the Itajaí-Açu River which is located in the north of the state of Santa Catarina (southern Brazil), and flows out to the Atlantic Ocean (Fig. 1). It is the largest river basin in the state, with an area of 15,111 km², corresponding to 25% of the total area of the state (Schettini et al. 1998). The mean river discharge is $228 \pm 282 \text{ m}^3 \text{ s}^{-1}$, therefore low discharge prevails most of the time, with short events of high discharge that usually exceed $1,000 \text{ m}^3 \text{ s}^{-1}$. The estuary of the Itajaí-Açu River presents highly stratified circulation, and the stratification is correlated with the rainfall, which presents a high seasonal and interannual variability (Schettini 2002), typical of the subtropical mesothermic wet climate.

The organisms were obtained from the Armação do Itapocoroy Bight ($26^{\circ}47'S-48^{\circ}36'W$), the largest mussel cultivation site in southern Brazil, nearly 20 km to the north of the study area, which was considered the control area (Fig. 1). This bight is influenced by the Brazil Current (temperatures higher than $26^{\circ}C$) during the summer and from the west boundary of the Subtropical Convergence Zone, and consequently, from the Falklands Current (temperatures lower than $17^{\circ}C$) during the winter (Carvalho et al. 1998). The salinity variation in Itapocoroy Bight is attributed to the Itajaí-açu River discharges (Schettini et al. 1999), which do not present any clear seasonal pattern in terms of flow rate. The seston is influenced by the resuspension of matter from the seabed, caused by the action of waves brought by the wind shear, mainly from the east (Resgalla and Schettini 2006).

Six groups of the mussel *P. perna* were transplanted at two points and three water depths off the Itajaí estuary inlet (Fig. 1). The period of exposure was ca. 50 days (January–March 2003), in the Austral Summer when higher precipitation levels are expected in the basin. Each group consisted

of 60 organisms with an average (\pm standard deviation) total length of $36.2 (\pm 2.3)$ mm. Taking into account the difficulties encountered in mooring independent systems, a navigation buoy was used (Point 1) and a hazard buoy (Point 2) to fix the organisms. Point 1 was 2 km from the inlet ($26^{\circ}54'38''S; 48^{\circ}37'23''W$) and Point 2 was 1.5 km from the inlet ($26^{\circ}55'15''S; 48^{\circ}37'23''W$), being 1.5 km apart. The mussel groups in the water column were packed in nylon bags, fixed by a steel cable anchored to the bottom sediment and suspended by a surface floating system. The groups were positioned in the water column at 9, 6, and 3 m below the surface. The aim of using the group fixed at a depth of 3 m was to avoid contact with the Itajaí Açu River freshwater plume, which is 2 m in depth. The groups at 9 m were almost 1 m above the bed on average, varying according to the tides. Additionally, one control group was fixed in Armação do Itapocoroy Bight and positioned only 1 m below the surface level under the same conditions described above and fixed according to the longline type system. This exposure placement was adopted to: (1) maintain control organisms under the same original conditions before introduction of transplanted groups; and (2) avoid contact of the control organisms with resuspended material from the bottom sediment due to the lower depth of the bight (7 m).

Vertical profiles of salinity, temperature and suspended particulate matter (SPM) were acquired at the control point and at the two points on five occasions during the exposure time, using a conductivity, temperature and depth recorder (CTD; Saiv A/S, model SD202) with an optical backscatter sensor to record the turbidity (Schettini et al. 2005). Estimates of the organic matter content of the SPM were carried out from water samples taken with a Niskin bottle, at the control and test points, at all transplantation depths, with laboratory analysis following the methodology of Strickland and Parsons (1972).

At the end of exposure time, three organisms from each control and test point and from all depths were frozen for later determination of the metals Fe, Mn, Pb, Zn, and Cr. The trace metal determination methods adhered to the recommendations of Greenberg et al. (1992) with the digestion of the whole soft tissue of the organisms in nitric acid under heating. The resulting solution was filtered and the volume determined was adjusted before analytical determination. Readings were taken on a Varian atomic absorption spectrophotometry (AAS), model Spectra AA/55, with a Varian steam generating accessory model VGA 77 and a Varian SIPS peristaltic sample introduction system. The detection limits for each metal were: $0.25 \text{ mg Fe kg}^{-1}$, $0.05 \text{ mg Mn kg}^{-1}$, $1.50 \text{ mg Pb kg}^{-1}$, $0.15 \text{ mg Zn kg}^{-1}$, and $0.15 \text{ mg Cr kg}^{-1}$.

The physiological rates of the mussels were estimated in the laboratory after a period of 24 h to acclimatize to the

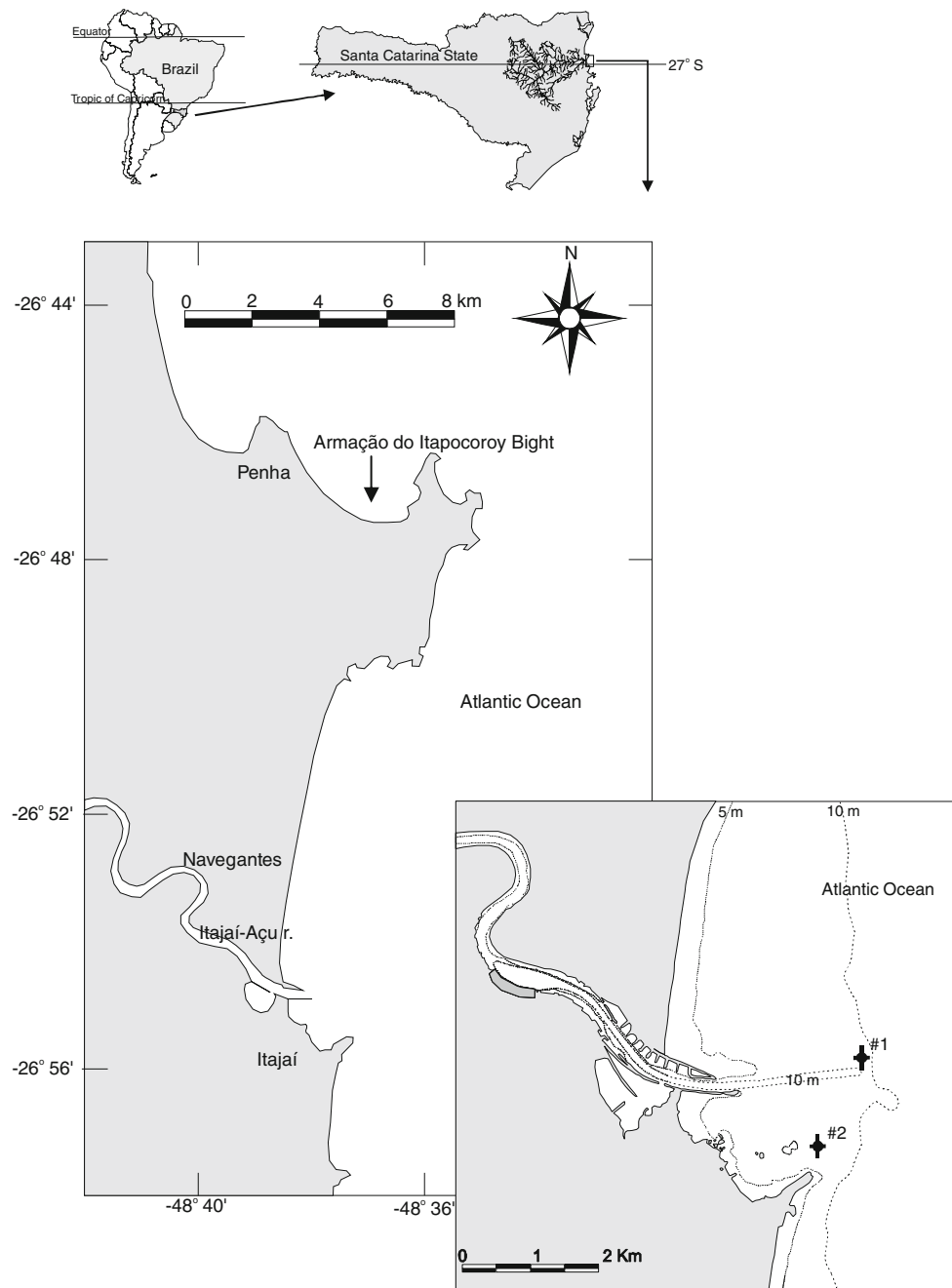


Fig. 1 Coast of Santa Catarina state (southern Brazil) with Armação do Itapocoroy Bight (control area) and mouth of the Itajaí-açu River, highlighting the two points of transplantation of the mussels (Points 1, 2) on nautical signaling buoys for ships entering the Port of Itajaí

filtered seawater at 20°C and a photoperiod of 12:12 (Resgalla et al. 2006). The clearance, respiration, excretion and absorption efficiency rates were calculated according to the methodology presented by Resgalla et al. (2006, 2007a).

The clearance rate was estimated in static form, in filtered seawater (0.5 µm), at constant temperature (20 ± 2°C) and with inoculation of a known concentration of a monospecific phytoplankton culture (*Chaetoceros gracilis*;

Smaal and Widdows 1994). The method consisted of estimating the removal rate of phytoplankton cells by the mussels in 1,000 mL test bottles, with 10 replicas (for each point and depth), one mussel per bottle, plus two control bottles without mussels. At the start and end of the experiment, with an incubation period of 1 h, 50 mL aliquots of incubation water were removed from the flasks and their fluorescence stimulated in a Turner Designs® fluorimeter

model TD-700. The clearance rate was estimated through the difference between the initial and final readings, with the application of the equation:

$$CR = \frac{V}{N} \left\{ \left[\frac{(\ln C_{t0} - \ln C_{t1})}{\Delta T} \right] - f \right\} \quad (1)$$

where CR, clearance rate ($l\ h^{-1}$); N , number of organisms per test flask (=1); V , volume of the test flask (l); $\ln C_{t0}$, natural logarithm of the fluorescence of the inoculated phytoplankton; $\ln C_{t1}$, natural logarithm of the fluorescence of the inoculated phytoplankton at time t ; ΔT , incubation period (h); f , Correction factor, calculated with the same formula as that used for the control flasks, and related to the decantation of the phytoplankton or the precision of the method.

The tests for respiration rates (RR) were carried out under the same conditions as those of the previous experiments, with two control bottles (no mussels) and ten test bottles containing one mussel per bottle (for each point and depth), incubated in filtered sea water without phytoplankton and under static conditions. The reduction of dissolved oxygen occurring in the flasks was measured using an YSI digital oxymeter model 58, for at least 3 h. Two readings were taken, one at the start and the other at the end of the test. The oxygen uptake by the mussels was calculated using the equation of Widdows and Johnson (1988):

$$RR = \left[(C_{t0} - C_{t1}) \times \frac{V}{\Delta T} \right] - f \quad (2)$$

where RR, respiration rate ($mL\ O_2\ h^{-1}$); $C_{(t0)}$, concentration of oxygen at time zero ($mL\ O_2\ L^{-1}$); $C_{(t1)}$, concentration of oxygen at end time ($mL\ O_2\ L^{-1}$); V , volume of the test flask (liters); ΔT , incubation time interval; f , Correction factor for the control flasks (calculated using the same formula as that described above, but in flasks not containing mussels).

To determine the excretion rate (ER), the organisms were kept immersed in 300 mL of filtered seawater at $0.5\ \mu m$, without inoculation of food (phytoplankton). At the initial time (T_0) and after 3 h (T_3), 15 mL samples of incubation water were collected to determine the total ammoniacal nitrogen, using the Merck Spectroquant® equipment and method. The increase in ammonium in the 10 test flasks (for each point and depth), and the 2 control flasks, enabled the ER to be estimated through the equation:

$$ER = \left[(C_{t1} - C_{t0}) \times \frac{V}{\Delta T} \right] - f \quad (3)$$

where ER, excretion rate ($\mu g\ NH_4^+\ h$); $C_{(t0)}$, concentration of ammonium at time zero; $C_{(t1)}$, concentration of ammonium at end time; V , volume of the test flask (liters); ΔT , incubation time interval; f , correction factor in the control

flasks (calculated by the formula given above, but in flasks without the presence of mussels).

The CR values were expressed in $L\ h^{-1}\ g^{-1}$ of dry weight of soft tissue of the test organisms (biomass) using a correction factor of $b = 0.48$, the RR values were expressed in $mL\ of\ O_2\ h^{-1}\ g^{-1}$ using a correction factor of $b = 0.66$, and the ER values were expressed as $\mu g\ N-NH_4\ h^{-1}\ g^{-1}$ using a correction factor of $b = 0.91$, as proposed by Resgalla et al. (2006).

The absorption efficiencies (AE) were determined under the same conditions as the tests for clearance rates, but with a duration of 24 h. The estimate proposed by Omori and Ikeda (1984) consisted of comparing the content of the organic matter present in the phytoplankton, with the organic matter eliminated in the feces collected in the bottom of the test flask. The proposed ratio was:

$$AE = \left[\frac{(I - F)}{1 - F} \times I \right] \times 100\% \quad (4)$$

where AE, absorption efficiency (%); I , percentage of organic matter in the food offered (phytoplankton); F , percentage of organic matter in the feces.

In order to improve the precision of the estimate, the feces produced by two organisms submitted to the same treatment were combined, totaling five replicates for the control area and for each depth for the two points in the study area. Three replicas of the aliquots of the phytoplankton culture were filtered, as was the feces collected, in fiberglass filters (GF/F) previously dried and weighed. After washing the filters, the dry weight of the material retained was estimated by drying in an oven at $60^\circ C$ for 12 h and placing in a desiccator for 8 h to obtain constant dry weight. The filters were calcinated in a muffle oven at $500^\circ C$ for 2 h (Strickland and Parsons 1972) to obtain the ash-free dry weight (organic matter).

The scope for growth (SFG) was estimated using the energy conversion factors presented by Bayne et al. (1985) and an organic matter mass of $2.1\ mg\ L^{-1}$ of phytoplankton used in the experiments, where $1\ mg\ of\ organic\ matter = 23.50\ J$; $1\ mL\ O_2\ respired = 20.33\ J$; $1\ \mu g\ N-NH_4^+ = 0.0249\ J$; and SFG was estimated in Joules, according to the equation:

$$SFG = [CR \times AE \times MS] - [RR + ER] \quad (5)$$

where SFG, scope for growth ($J\ h^{-1}\ g^{-1}$); CR, clearance rate ($L\ h^{-1}\ g^{-1}$); AE, absorption efficiency (%); MS, Seston in weight of organic matter ($J\ L^{-1}$); RR, respiration rate ($J\ h^{-1}\ g^{-1}$); ER, excretion rate ($J\ h^{-1}\ g^{-1}$).

The relationship between respiration and excretion (O:N ratio) was estimated to determine the nutritional state of the organisms in relation to the different conditions in which they were maintained and to compare with the SFG (Bayne et al. 1985).

The growth rates (mm day^{-1}) of the mussels in the control and study areas were estimated through the difference between the average total length at time zero (before transplantation) and after maintaining them at the transplantation site for a period of time.

The data for the physiological rates of the different groups of mussels were compared using analysis of variance (ANOVA), and the Bonferroni *t*-test *a posteriori* according to Zar (1996). For the comparison of physiological rates, only data from the experiments in which the organisms showed high activity were used, according to the recommendations of Smaal and Widdows (1994).

Results

Table 1 gives the environmental data for the three points at which the mussels were fixed, as averages of the five samples obtained after *ca.* 50 days of exposure time. Salinity and temperature variations between Points 1 and 2 (for the three water depths) were not pronounced, while a considerable variation was observed in the SPM values for the two points. For the point located at the mouth of estuary (Point 2) the SPM values increased with increasing depth from the surface, with SPM values for Point 2 (mean for

the water column of 5.79 mg L^{-1}) being higher than those for Point 1 (mean for the water column of 3.32 mg L^{-1}), while the control point showed intermediate SPM values.

The analysis of mussel tissue for trace metals did not indicate major differences between the control area and study area for Pb and Zn (Table 2). In spite of the low number of samples analyzed, there is a clear tendency of transplanted organisms from Point 1 (at 3 m depth) and Point 2 (at 9 m depth) to accumulate the metals Fe, Mn and Cr. In the same manner, a tendency toward changes in the physiological rates of the mussels from the transplantation points compared with the control area was observed (Table 3). In this regard, the mussels from Point 2 showed a 15.7% decrease in the absorption rate and a 282.5% increase in the excretion rate for the organisms placed at greater depth (9 m). These mussels showed reductions of 28.8% in the clearance rate and 55.6% in the O:N ratio, resulting in a 48.6% decrease in the SFG compared with the organisms from the control area. Table 1 shows that mussels from all groups studied had the same decreasing tendency for the growth rate. On the other hand, the mussels transplanted at Point 1 showed the lowest RR and the lowest energy expense. No mortality was observed in any case during the experimental exposure.

Table 1 Average and standard deviation values for temperature, salinity, suspended particulate matter (SPM), organic matter content of the SPM (OM) of the water from five sampling events and growth rate (GR) of the mussels obtained after *ca.* 50 days of exposure time at the control site (Armação do Itapocoroy Bight at 1 meter depth) and at the two test points of the Itajaí-açu River mouth at three different depths

| | | Temperature ($^{\circ}\text{C}$) | Salinity (ppt) | SPM (mg L^{-1}) | OM (%) | GR (mm day^{-1}) |
|---------|-----|------------------------------------|------------------|----------------------------|------------------|-----------------------------|
| Control | 1 m | 26.65 ± 0.72 | 32.31 ± 0.75 | 3.51 ± 1.31 | 30.56 ± 4.63 | 0.133 |
| Point 1 | 3 m | 26.18 ± 0.52 | 33.35 ± 0.84 | 1.53 ± 0.76 | 35.85 ± 5.65 | 0.243 |
| | 6 m | 25.92 ± 0.54 | 33.57 ± 0.85 | 2.36 ± 1.18 | 31.12 ± 6.16 | 0.209 |
| | 9 m | 25.82 ± 0.49 | 34.75 ± 0.74 | 6.08 ± 1.67 | 21.30 ± 2.56 | 0.145 |
| Point 2 | 3 m | 26.01 ± 0.33 | 32.82 ± 1.29 | 3.55 ± 2.15 | 27.20 ± 5.80 | 0.145 |
| | 6 m | 26.25 ± 0.59 | 33.43 ± 0.95 | 4.15 ± 2.70 | 26.25 ± 6.62 | 0.124 |
| | 9 m | 25.81 ± 0.45 | 33.56 ± 0.87 | 9.66 ± 4.03 | 18.33 ± 3.37 | 0.100 |

Table 2 Average concentration (mg kg^{-1} of wet weight) and standard deviation of trace metals in the tissues of the mussel *Perna perna* in the control area and after *ca.* 50 days of exposure in the mouth of the Itajaí-açu River, at two points and at three transplantation depths ($n = 3$)

| Metals | Control | Point 1 | | | Point 2 | | |
|--------|----------------|------------------|----------------|-----------------|-----------------|-----------------|-----------------|
| | | 3 m | 6 m | 9 m | 3 m | 6 m | 9 m |
| Pb | ND | ND | ND | ND | ND | ND | ND |
| Cr | ND | 0.17 ± 0.17 | ND | 0.15 ± 0.13 | 0.05 ± 0.09 | 0.07 ± 0.11 | 0.21 ± 0.18 |
| Fe | 11.3 ± 0.9 | 102.8 ± 57.7 | 40.4 ± 6.8 | 57.4 ± 21.6 | 39.3 ± 11.8 | 43.0 ± 6.8 | 90.6 ± 42.2 |
| Mn | 0.6 ± 0.4 | 3.0 ± 1.0 | 1.3 ± 0.2 | 1.8 ± 0.3 | 1.9 ± 0.7 | 1.4 ± 0.4 | 2.3 ± 0.7 |
| Zn | 16.5 ± 3.3 | 14.1 ± 1.2 | 15.3 ± 0.8 | 16.2 ± 2.0 | 14.4 ± 1.7 | 15.9 ± 3.1 | 14.2 ± 2.3 |

ND not detected

Table 3 Average and standard deviation values for the physiological rates of mussels in the control area and after *ca.* 50 days transplanted at two points in the Itajaí-açu River mouth, at different depths

| | CR | RR | ER | AE | O:N | SFG |
|-----------|--------------|--------------|-----------------|----------------|----------------|---------------|
| Control | 1.84 ± 0.51 | 0.63 ± 0.08 | 45.32 ± 43.20 | 84.68 ± 2.48 | 42.86 ± 12.39 | 61.75 ± 20.68 |
| Point 1 | | | | | | |
| 3 m | 2.32 ± 0.54 | 0.55 ± 0.06* | 53.62 ± 14.51 | 81.16 ± 5.14 | 28.47 ± 6.61 | 67.05 ± 9.91 |
| 6 m | 1.94 ± 0.25 | 0.50 ± 0.02* | 64.20 ± 19.50 | 85.25 ± 2.36 | 21.22 ± 9.62 | 72.81 ± 7.38 |
| 9 m | 2.06 ± 0.60 | 0.47 ± 0.03* | 85.04 ± 30.89* | 83.61 ± 5.07 | 25.36 ± 11.63 | 79.07 ± 10.81 |
| Point 2 | | | | | | |
| 3 m | 1.70 ± 0.33 | 0.59 ± 0.03 | 54.29 ± 36.53 | 68.40 ± 2.32* | 31.99 ± 11.03 | 46.01 ± 8.99 |
| 6 m | 2.13 ± 0.14 | 0.58 ± 0.01 | 98.03 ± 26.38* | 71.64 ± 6.85* | 28.72 ± 10.22 | 58.08 ± 7.71 |
| 9 m | 1.31 ± 0.20* | 0.60 ± 0.02 | 128.04 ± 46.68* | 71.37 ± 10.63* | 19.03 ± 13.64* | 31.73 ± 4.90* |
| <i>F</i> | 3.977 | 10.668 | 4.105 | 5.644 | 2.240 | 19.709 |
| <i>df</i> | 6,28 | 6,28 | 6,27 | 6,27 | 6,25 | 6,29 |

CR clearance Rate ($L h^{-1} g^{-1}$), RR respiration Rate ($mLO_2 h^{-1} g^{-1}$), ER excretion Rate ($\mu gN-NH_4 h^{-1} g^{-1}$), AE absorption efficiency (%), O:N O:N ratio and SFG scope for growth based on $2.1 mg L^{-1}$ of organic matter of the phytoplankton used in the experiments ($J h^{-1} g^{-1}$)

* The results of the analysis using ANOVA and Bonferroni *t*-test *a posteriori*, for the control and test points/depths, for a significance level of $P < 0.05$. *F* Fisher value, *df* degree of freedom (v_1, v_2)

Discussion

Despite the proximity of the two transplantation points and similarity of the hydrographic conditions (salinity and temperature), Point 2 presented a higher concentration of SPM. The similar hydrography indicates that the two stations are subject to the same water masses at the same time. However, the hydrodynamic conditions of the stations are not necessarily the same. Point 1 is located in front of the estuary mouth, in the access channel of the port, while Point 2 is closer to the coast, although both are a similar distance from the river mouth (Fig. 1). However, the hazard buoy at Point 2 indicated the presence of submersed shallow rocks, which potentially increases the interaction of the currents and waves with the sediment. This interaction of the seabed with the waves can lead to resuspension of sediments, while the currents help retain these sediments in the water column. Since Point 1 is subjected to a lower sediment resuspension, organic matter can accumulate at this point, values being near those observed in the control bight.

The greater hydrodynamics at Point 2 can lead to the maintenance of higher levels of metals in the water column, due to the suspension of the metal-rich sediment, with a greater influence on the organisms closer to the bed. This hypothesis is based on observation of the concentrations of Fe and Mn in the tissues of the organisms placed at 9 m depth. Likewise, the Cr concentration in the organism tissue showed a tendency to increase in relation to the control area. According to Rörig (2005), Cr is an important contaminant in the Itajaí-Açu River and it is responsible for the observed toxicity of the sediment toward sea urchins and

mysidacea (Laitano and Resgalla 2000). But this metal alone cannot explain the variations observed in the physiological rates of the organisms studied, as the concentrations obtained in the tissues of the mussels collected from the two transplantation points did not show variations.

The coastal region bottom sediment enrichment of trace metals is likely to originate from the contribution of the Itajaí-açu River through the buoyant plume (tissue accumulation in Point 1 at depth of 3 m) and dredging activity in the harbor as potential sources. The maintenance dredging of the access channel and turning basin of the Port of Itajaí is carried out using a water injection system dredge. The dredging is quasi-continuous, in order to keep the bed unconsolidated, generally being carried out for 3–4 days every spring tide, preferentially during the ebb. The fate of the dredged material has not yet been assessed but it may have a significant ecological influence on the coastal region close to the river mouth.

The variability observed in the physiological rates of the mussels can be attributed to four factors: salinity, temperature, availability of food in the form of SPM, and the presence of contaminants. Variations in the physiological rates of the mussel *P. perna* due to salinity and temperature have previously been investigated by Resgalla et al. (2007a) and no significant alterations were observed with values of 25–35 for salinity and 20–25°C for the temperature.

Regarding the organic material available as food, Point 2 had the highest concentrations, mainly near the bed. However, the organic matter was diluted to a higher proportion with the inorganic fraction, which would lead to higher clearance rates and lower absorption efficiency, but with no effect on the respiration and excretion rates

(Resgalla et al. 2007b). With the exception of absorption efficiency, the other physiological rates did not behave in the expected manner in terms of SPM variation and their percentage of organic matter.

The results suggest that the organisms transplanted at Point 1 (in front of the river mouth) were under conditions of less stress (lower respiration rate) than the organisms at Point 2. For this second point, the rate relating to the obtaining of energy (AE) was lower and the excretion rates (ER—loss of energy) were higher than those obtained for the control area. A decrease was also observed in the SFG at a transplantation depth of 9 m, i.e., closer to the bottom. These results have the same trend as the growth rate data (Table 1).

It is hypothesized that the source of contamination of the organisms is the sediment, although the nature of the contaminant responsible for the alterations in the physiological rates of the mussels is unknown. However, the analysis of the tissue carried out on the samples obtained before transplantation suggests that Cr is responsible for these alterations. As an essential trace metal, Cr should be easily regulated by the organism, but in the presence of other trace metals and over a long period of exposure to contaminants, this regulating capacity may be lost (Bellotto and Francioni 2008).

The effects of metals on the physiological rates of mussels in the environment have been investigated by several authors and for different species (Martin et al. 1984; Widdows and Donkin 1992; Smaal and Widdows 1994). A reduction in CR and SFG is normally reported in these studies, associated with an increase in the concentration of trace metals in the tissues. However, variability according to the type of contaminant, concentration in the environment, and exposure time of the mussels has also been observed (Widdows et al. 1997).

Laboratory experiments carried out on the physiological rates of *P. perna* exposed to trace metals have also indicated variability in the responses (Resgalla and Moraes 2008) and the metabolic parameters normally affected in bivalves are the clearance rates (Widdows and Johnson 1988) and excretion rates (Bayne et al. 1985), as observed by Watling and Watling (1982) with a reduction in CR under the effect of Cr. According to Pessatti et al. (2002), sub-lethal concentrations of Pb could stimulate the CR and inhibit the RR of *P. perna*, however, under conditions where other trace metals are also present and/or with longer exposure times the CR may be inhibited (Resgalla and Moraes 2008).

All these points suggest that the organisms transplanted at Point 2 and close to the bottom were exposed to sub-lethal concentrations of trace metals, altering the energy balance and the SFG. However, the presence and tissue concentrations of Cr are not sufficient to explain this stress, since this element is also present in the transplanted

organisms at Point 1. Thus, it is probably that other non-quantified contaminants may be acting synergistically on the organisms, causing the alterations observed in this study.

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References

- Bayne BL, Brown DA, Burns K, Dixon DR, Ivanovici A, Livingstone DR, Lowe DM, Moore MN, Stebbing ARD, Widdows J (1985) The effects of stress and pollution on marine animals. Praeger Publishers, New York
- Bellotto VR, Francioni E (2008) Capítulo 13—Níveis de metais e sua aplicação na análise e monitoramento ambiental. In: Resgalla C Jr, Weber LI, Conceição MB (eds) O mexilhão *Perna perna*: Biologia, Ecologia e Aplicações. Editora Interciência, Rio de Janeiro, pp 207–235
- Carvalho JLB, Schettini CAF, Ribas TM (1998) Estrutura termohalina do litoral centro-norte catarinense. Notas Téc FACIMAR 2:181–197
- Clements WH, Kiffney PM (1994) Integrated laboratory and field approach for assessing impacts of heavy metals at the Arkansas River, Colorado. Environ Toxicol Chem 13:397–404
- Gommersbach VB (2000) Monitoramento da qualidade da água em rios a partir de imagens orbitais. Estudo de caso: rio Itajaí-açu. MSc. Dissertation. Fundação Universidade de Blumenau, Brazil
- Greenberg AE, Clesceri LS, Eaton AD (1992) Standard methods for the examination of water and wastewater. APHA, Washington
- Laitano K, Resgalla C Jr (2000) Uso de testes de toxicidade com larvas de *Arbacia lixula* e juvenis de *Metamysidopsis elongata atlantica* na avaliação da qualidade do sedimentos dos rios Camboriú e Itajaí-Açú (Santa Catarina). In: Espíndola G, Botta Paschoal CMR, Rocha O et al (eds) Ecotoxicologia. Perspectivas para o século XXI. Rima Editora, São Carlos, pp 29–42
- Martin M, Ichikawa G, Goetzl J, Reyes M, Stephenson MD (1984) Relationships between physiological stress and trace toxic substances in the Bay Mussel, *Mytilus edulis*, from San Francisco Bay, California. Mar Environ Res 11:91–110
- Omori M, Ikeda T (1984) Methods in marine zooplankton ecology. John Wiley, New York
- Pereira Filho J, Spillere LC, Schettini CAF (2003) Dinâmica de nutrientes na região portuária do estuário do rio Itajaí-Açú, SC. Atlântica 25:11–20
- Pessatti M, Resgalla C Jr, Reis Filho RW, Kuehn J, Salomão LC, Fontana JD (2002) Variability of filtration and food assimilation rates, respiratory activity and multixenobiotic resistance (MXR) mechanism in the mussel *Perna perna* under lead influence. Braz J Biol 62(4):651–656
- Rand GM (1995) Fundamentals of aquatic toxicology. Effects, environmental fate and risk assessment. Taylor & Francis, Washington
- Resgalla C Jr, Schettini CAF (2006) Características e variação do seston da enseada da Armação do Itapocoroy, Penha, SC. In: Branco JO, Marenzi AWC (eds) Bases ecológicas para um

- desenvolvimento sustentável: estudos de caso em Penha. SC. Editora UNIVALI, Itajaí, pp 107–120
- Resgalla C Jr, Moraes RBC (2008) Capítulo 15—uso em ensaios ecotoxicológicos. In: Resgalla C Jr, Weber LI, Conceição MB (eds) *O mexilhão Perna perna: biologia, ecologia e aplicações*. Editora Interciência, Rio de Janeiro, pp 253–268
- Resgalla C Jr, Brasil ES, Salomão LC (2006) Physiological rates in different classes of sizes of *Perna perna* (Linnaeus, 1758) submitted to experimental laboratory conditions. *Braz J Biol* 66:325–336
- Resgalla C Jr, Brasil ES, Salomão LC (2007a) The effect of temperature and salinity on the physiological rates of the mussel *Perna perna* (Linnaeus 1758). *Braz Arch Biol Technol* 50:543–556
- Resgalla C Jr, Brasil ES, Salomão LC (2007b) Efeito da concentração e da qualidade do alimento nas taxas fisiológicas do mexilhão *Perna perna* (Linnaeus, 1758). *Atlântica* 29:47–59
- Rörig LR (2005) Uso múltiplos e qualidade das águas da baía do baixo Itajaí-açu, SC. Elementos para um gerenciamento integrado. PhD thesis, Universidade Federal São Carlos, Brazil
- Schettini CAF (2002) Caracterização física do estuário do rio Itajaí-açu, SC. *Rev Bras Recursos Hídricos* 7(1):123–142
- Schettini CAF, Toldo EE Jr (2006) Fine sediment transport modes in the Itajaí-Açu estuary, southern Brazil. *J Coastal Res* 39 (SI):515–519
- Schettini CAF, Kuroshima KN, Pereira Filho J, Rörig LR, Resgalla C Jr (1998) Oceanographic and ecological aspects of the Itajaí-Açu River plume during a high discharge period. *An Acad Bras Ciênc* 70(2):335–351
- Schettini CAF, Carvalho JLB, Truccolo EC (1999) Aspectos hidrodinâmicos da enseada da Armação do Itapocoroy, SC. *Notas Téc FACIMAR* 3:99–109
- Schettini CAF, Resgalla C Jr, Pereira Filho J, Silva MAC, Truccolo EC, Rörig LR (2005) Variabilidade temporal das características oceanográficas e ecológicas da região de influência fluvial do rio Itajaí-Açu. *Braz J Aquatic Sci Technol* 9(2):93–102
- Schettini CAF, Ricklefs K, Truccolo EC, Golbig V (2006) Synoptic hydrography of a highly stratified estuary. *Ocean Dyn* 56(3–4): 308–319
- Smaal AC, Widdows J (1994) Chapter 2—the scope for growth of bivalves as an integrated response parameter in biological monitoring. In: Kramer KJM (ed) *Biomonitoring of coastal waters and estuaries*. CRC, Boca Raton, pp 247–267
- Strickland JDH, Parsons TR (1972) A practical handbook of seawater analysis. *Bull Fish Res Board Canada* 167:310
- Trochimczuk A, Schettini CAF (2003) Avaliação da dispersão especial da pluma do estuário do Rio Itajaí-Açu em diferentes períodos de descarga. *Notas Téc Facimar* 7:83–96
- Watling HR, Watling RJ (1982) Comparative Effects of Metals on the Filtering Rate of the Brown Mussel (*Perna perna*). *Bull Environ Contam Toxicol* 29:651–657
- Widdows J, Johnson D (1988) Physiological energetics of *Mytilus edulis*: scope for growth. *Mar Ecol Prog Series* 46:113–121
- Widdows J, Donkin P (1992) Chapter 8—mussel and environmental contaminants: bioaccumulation and physiological aspects. In: Gosling E (ed) *The mussel Mytilus edulis: ecology, physiology, genetics and culture*. Elsevier, Amsterdam, pp 383–424
- Widdows J, Nasci C, Fossato U (1997) Effects of pollution on the scope for growth of mussels (*Mytilus galloprovincialis*) from the Venice lagoon, Italy. *Mar Environ Res* 43(1/2):69–79
- Zar JH (1996) *Biostatistical analysis*. Prentice Hall, New Jersey