Invertebrate Reproduction and Development, 44:1 (2003) 9–15
Balaban, Philadelphia/Rehovot
0168-8170/03/$05.00

Population dynamics of *Acartia clausi* from a temperate estuary (Mondego Estuary, Western Portugal)

LUÍS VIEIRA[1], FERNANDO MORGADO[2], PEDRO RÉ[3], ANTÓNIO NOGUEIRA[2], RAMIRO PASTORINHO[2], MÁRIO PEREIRA[2], PAULA BACELAR-NICOLAU[1], JOÃO CARLOS MARQUES[1] and ULISSES MIRANDA AZEITEIRO[1*]

[1]*IMAR – Instituto do Mar, Universidade de Coimbra, 3004-517 Coimbra, Portugal*
[2]*Departamento de Biologia, Universidade de Aveiro, 3810-193 Aveiro, Portugal*
[3]*IMAR – Instituto do Mar, Laboratório da Guia, 2750 Cascais, Portugal*

Received 30 March 2002; Accepted 13 March 2003

Summary

The main purpose of this study was to estimate the distribution, production and production/biomass ratio values of *Acartia clausi*, one of the most representative taxa of the Copepoda community in the Mondego estuary. The following biomass/length relationship was estimated for specimens of *Acartia clausi*: AFDW = 2.27 $BL^{2.41}$. Length–weight relationships were used to estimate production taking into account cohort growth and mortality. The annual production was calculated at 63.44 mgC $m^{-3}y^{-1}$ and the production/biomass ($P/\overline{B}$) ratio was estimated at 25.50. These results indicate that *Acartia clausi* may play a significant role in transferring energy to higher trophic levels in the Mondego estuarine system.

Key words: *Acartia clausi*, biometry, image analysis, production, zooplankton, estuaries

Introduction

Copepoda (Crustacea) comprise the most abundant taxa of the estuarine and marine zooplankton (Omori and Ikeda, 1984; Kennish, 1990; Mackas, 1992; Sautour and Castel, 1995). There they act as an efficient and direct path for energy transfer to higher trophic levels (Bond, 1994; Williams et al., 1994) and contribute substantially to the downward flux of organic material (Feinberg and Dam, 1998).

Biomass estimates for copepoda species in an estuarine ecosystem provide useful information on the energy flux, and such measurements are essential in ecological studies. For zooplankton, the literature reports suitable coefficients, which, starting from linear measurements of body dimensions (Tackx et al., 1995), reveal the weight or carbon contents of the specimens studied (Krylov, 1968; Pertsova, 1966; Shmeleva, 1965; Uye, 1982). These studies have become easier to carry out thanks to image analysis methods (Christou and Verriopoulos, 1993; Jeffries, 1998).

The copepoda community of the Mondego estuary is dominated by the *Acartia* genus (Copepoda: Calanoida) (Azeiteiro et al., 1999, 2000; Vieira et al., 2003). *Acartia clausi* Giesbrecht is a euryaline

*Corresponding author at: Universidade Aberta, Delegação Norte, Rua do Ameal, 752, 4200-055 Porto, Portugal. Fax: +351 (22) 830-0249; email: ulisses@univ-ab.pt.

temperate-boreal species (Lee and McAlice, 1979) very common in the Portuguese coastal ecosystems — in both estuarine and coastal waters (Morgado, 1997; Azeiteiro et al., 1999, 2000; Pardal and Azeiteiro, 2001; Vieira et al., 2003). *A. clausi* has been identified as a common copepod in the Mondego estuary (Azeiteiro et al., 1999, 2000; Vieira et al., 2003) that is present in the plankton throughout the year (Azeiteiro et al., 1999, 2000; Vieira et al., 2003).

The main purpose of this study was to estimate the distribution, production and production/biomass ratio values of *A. clausi*.

Materials and Methods

Study site

The Mondego River estuary, located on the Portuguese west coast (40°08′N, 8°50′W), has an area of 3.3 km^2 and a volume of 0.0075 km^3. The hydrological basin of the Mondego, with an area of 6670 km^2, provides an average discharge of 8.5×10^9 m^3s^{-1}. The circulation in the south arm of the estuary (where the sampling station is located) depends on the tides and in a much smaller amount on the freshwater discharge from a tributary, the Pranto River, which is controlled by a sluice located 3 km from the confluence with the Mondego River. The sampling station was located in the southern arm of the estuary (Fig. 1), closest to the mouth of the estuary.

Determination of environmental parameters

Water samples were taken monthly, from July 1999 to June 2000; and salinity, temperature, dissolved oxygen and pH were measured *in situ*. Samples were also analysed in the laboratory (in triplicate) (Bacelar-Nicolau et al., 2003) for their content in nitrate, nitrite, ammonium, phosphate and chlorophyll *a* concentration (Strickland and Parsons, 1972).

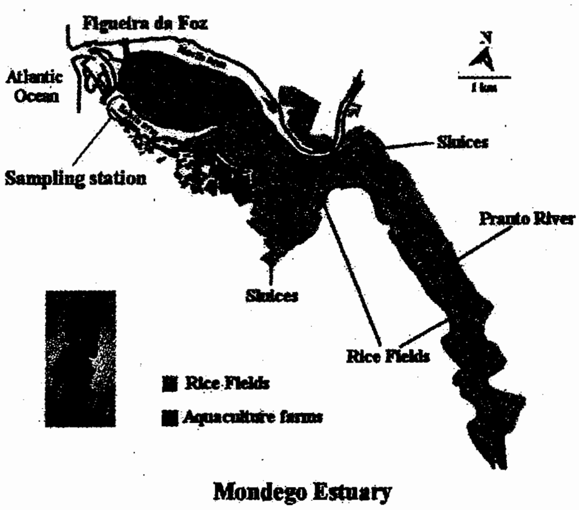

Fig. 1. Map of the Mondego estuary showing the location of the sampling station in the south arm.

Zooplankton sampling

Samples were taken monthly from July 1999 to June 2000. Sub-surface samples were collected during high spring tides using two different nets, 63 and 125 mm mesh size net, in order to obtain samples contained organisms with the wide size spectrum (Vieira et al., 2003).

Data analysis

Multivariate regression analysis (STEPWISE) was applied to find an explanatory model for the dynamics of the *A. clausi* population in terms of the environmental parameters monitored (temperature, salinity, dissolved oxygen, pH and chlorophyll *a*).

Production study methodology

A. clausi individuals were counted and measured by image analysis (Billones et al., 1999; Tackx et al., 1995). The conversion to biovolumes and to carbon weights was done by the expressions and using the conversion factors given by Billones et al. (1999). Body volumes were calculated from lengths and width measurements as an ellipsoid using the following formula:

$$V_B = \frac{4}{3}\pi\frac{L}{2}\left(\frac{W}{2}\right)^2$$

where V_B is the volume of body, W the width of body, and L is the length of body, converted into carbon weight using the following conversion factors:

- 10^6 mm^3 body volume = 1 mg wet weight (Omori and Ikeda, 1984)
- dry weight = 20% wet weight (Billones et al., 1999)
- carbon weight = 45% dry weight (Heinle et al., 1977; Bernard, 1958).

The relationship between total length and ash-free dry weight (AFDW) was also established and used in production estimates.

Growth (P_c) production for each cohort for a given time interval was estimated as:

$$P_c = \left[(N_t + N_{t+1})/1\right]\left(\overline{W}_{t+1} - \overline{W}_t\right) \quad \text{for } \overline{W}_{t+1} > \overline{W}_t$$

where N is the number of individuals from a cohort at each sample date, $\overline{W}$ the mean individual biomass for each sample date, and t and t+1 the consecutive sampling dates (Allen, 1971).

Total value of P for each cohort is expressed as:

$$P_c = \sum_{t=0}^{n} \left[(N_t + N_{t+1})/2\right] \Delta \overline{W}$$

where n is the sampling month. The total production for the population (P) is expressed as:

$$P = \sum P_c$$

The $P/\overline{B}$ ratio was determined. Mean population biomass is expressed as:

$$\overline{B} = (1/T) \sum_{n=1}^{N} \left(\overline{B}_n \times t\right)$$

where T is the period of study, N the number of cohorts in period T, $\overline{B}_n$ the mean biomass of the cohort n and t the duration of the cohort n.

Results

Seasonal variation in environmental variables

The environmental parameters over the 11-month study (July 1999–June 2000) are shown in Table 1.

Acartia clausi *abundance*

The copepoda 63 µm taxocenosis, in terms of species composition, was dominated by estuarine and estuarine/neritic copepods, *A. clausi* being one of the most abundant species, including adult and copepodits. *A. clausi* copepodit abundance varied significantly throughout the months of the year (0.05>P>0.01) and presented high densities in January (2331 ind.m^{-3}) and April (1623 ind.m^{-3}) (Vieira et al., 2003). The copepoda 125 µm taxocenosis, in terms of species composition, was also dominated by estuarine and estuarine/neritic copepods, the adults of *A. clausi* being one of the most abundant species. *A. clausi* adults presented a peak of abundance in April (560 ind.m^{-3}) (Vieira et al., 2003).

Multiple regression analysis

Multiple regression analysis (STEPWISE) (r = 0.990; r^2 = 0.981) (Table 2) indicated that the abundance of *A. clausi* increases with increasing salinity and temperature.

Length–weight relationships

The following biomass/length relationship was estimated for specimens of *A. clausi* (Fig. 2): AFDW = 2.27 BL$^{2.41}$ with an r^2 of 0.5817, provided from 251 individuals measured and weighed. Size–frequency polymodal distributions were analysed for *Acartia clausi* recognisable cohorts (Fig. 3).

Production

Length–weight relationships were used to estimate production taking into account cohort growth and mortality. The annual production was calculated at

Table 1. Environmental parameters (temperature, salinity, pH, oxygen dissolved saturation %, NO_2^-, NO_3^-, NH_3, PO_4^{3-} and chlorophyll *a* values) from the monthly annual sampling cycle in the south arm of the Mondego estuary, between July 1999 and June 2000

	Temp., °C	Salinity, ‰	pH	% DO_2	NO_2, mg L^{-1}	NO_3, mg L^{-1}	NH_3, mg L^{-1}	PO_4, mg L^{-1}	Chlorophyll *a*
Jul	18.9	24.5	8.2	80.0	0.006	0.065	0.002	0.004	0.605
Aug	20.0	23.0	8.1	94.0	0.006	0.058	0.008	0.004	0.415
Sept	19.1	25.0	8.3	86.0	0.006	0.051	0.015	0.004	0.250
Oct	16.9	27.0	7.6	80.5	0.009	0.085	0.003	0.003	1.080
Nov	16.8	31.1	7.9	68.4	0.007	0.073	0.007	0.003	0.670
Dec	11.8	17.9	7.8	69.5	0.005	0.061	0.010	0.003	0.260
Jan	11.9	23.2	7.9	89.5	0.005	0.129	0.032	0.003	0.190
Feb	14.1	29.7	7.9	99.4	0.008	0.16	0.045	0.004	0.340
Mar	—	—	—	—	—	—	—	—	—
Apr	14.2	31.	7.5	85.0	0.008	0.171	0.040	0.003	0.810
May	15.8	21.1	7.7	97.4	0.007	0.178	0.034	0.003	0.740
Jun	18.0	26.1	8.2	66.0	0.012	0.091	0.093	0.003	0.620

Table 2. Variables in the equation of multiple regressions for the variation of the abundance of *Acartia clausi* over the sampling period (r = 0.990; r^2 = 0.981) (P<0.0001)

Variables	Regression coefficient	Standard deviation of the regression coefficient
Chlorophyll *a*	−0.308	0.110
DO	−0.006	0.066
pH	−1.008	0.047
Salinity	0.033	0.067
Temperature	0.020	0.085

63.44 mgC $m^{-3}y^{-1}$ and the production/biomass ($P/\overline{B}$) ratio was estimated at 25.50.

Discussion

The distribution patterns of the environmental parameters observed are mostly in agreement with previous studies (Bacelar-Nicolau et al., 2003). During the study period, *A. clausi* was positively correlated with salinity and temperature according to the species preferences (Alcaraz, 1983).

Table 3. Copepoda production and production/biomass ratio values data

Species	Reference	Study site	Methods	*P* (annual)	*P/B*
Acartia spp.	Hirst et al., 1999	1	Weight	17.62 mgC m^{-3} y^{-1}	
Acartia bifilosa	Irigoien and Castel, 1995	2	Size		28
Acartia spp.	Escaravage and Soetaert, 1995	3	Growth rate	5 g C m^{-2} y^{-1}	
Copepoda	Hirst et al., 1999	1	Weight	32.2 mgC m^{-3} y^{-1}	
Eurytemora spp.	Escaravage and Soetaert, 1995	3	Growth rate	6 gC m^{-2} y^{-1}	
Paracalanus parvus and *Pseudocalanus elongatus*	Hirst et al., 1999	1	Weight	1.67 mgC m^{-3} y^{-1}	
Temora longicornis	Hirst et al., 1999	1	Weight	4.77 mgC m^{-3} y^{-1}	
Acartia tonsa	Pastorinho et al., 2003	4	Cohorts	23 mg C m^{-3} y^{-1}	29
Acartia bifilosa var inermis	Vieira et al., 2002	4	Cohorts	43.12 mgC m^{-3} y^{-1}	11

Sites: 1 Coastal station, Solent, UK; 2 The Gironde, SW France; 3 Westerschelde estuary, The Netherlands; 4 Mondego estuary, Portugal.

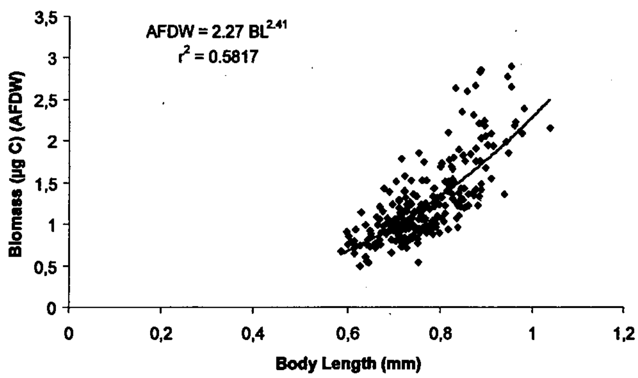

Fig. 2. Regression model for biomass–length relationships of *Acartia clausi* in the Mondego estuary. Correlation coefficient (r^2) is indicated.

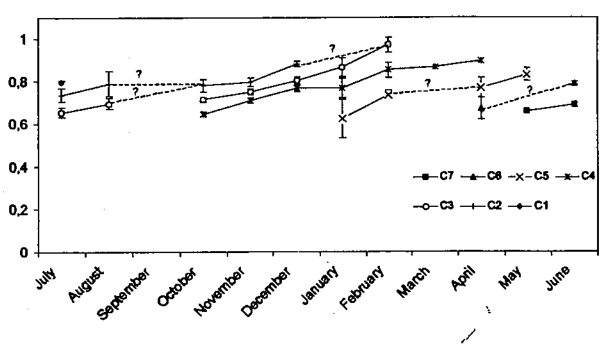

Fig. 3. Estimated growth of *Acartia clausi* cohorts, average total length ± standard deviation during the study period.

Table 4. Number of generation's values

No. of generations	Study site	Reference
2	Occidental Atlantic	Deevey, 1971
3,4	Adriatic Sea	Vucetic, 1957
4	Roscoff	Razouls, 1965
4	Long Island Sound	Conover, 1956
5	Plymouth	Digby, 1950
6,7	Sebastopol	Greze and Baldina, 1972
8	Black Sea	Porumb, 1968
9	Karadag	Tchaianova, 1950
Continuous	Mediterranean	Bernard, 1958

The morphometrics (Christou and Verriopoulos, 1993) and production value estimated in this study are in accordance with values reported by other authors (Table 3) to the species, the genus and other Copepoda species. The $P/\overline{B}$ value obtained has given us an expected modal turnover rate (Valiela, 1995; Banse and Mosher, 1980). This value means that, although the biomass of small-sized species may be small, the higher specific production makes them important producers. The obtained results indicate that *A. clausi* may play a significant role in transferring energy to higher trophic levels. Although production by nauplii is not included in the present study, this does not typically exceed 25% of copepod total production (Liang et al., 1996; Liang and Uye, 1996).

Most copepods reproduce throughout the year. The cohorts represent the maximum of generations possible and the duration of the cohorts represents the longevity of the generations (Binet, 1977). Copepoda life cycles in temperate regions have an average of 25 to 45 days. In temperate regions adult longevity rarely exceeds 2 months (Gaudy, 1972). In our study seven annual growth generations were found. Similar results were reported for other systems at the same latitude (Table 4: Plymouth, Digby, 1950; Sebastopol, Greze and Baldina, 1972 and Black Sea, Porumb, 1968); in the same table a clear latitudinal variation is evident. The most notable aspect different in this study is the longer longevity found in the Mondego estuary, also attributable to other species of the genus (*A. tonsa* and *A. bifilosa* var *inermis*) found in the estuary (Pastorinho et al., 2003; Vieira et al., 2002). Both temperature and food availability are known to play a significant role in copepod production activity and life cycle (Klein and Gonzalez, 1988; Kleppel, 1992). Biological cycle and annual generations depend on latitude, temperature and trophic availability (Gaudy, 1972) and in the Mondego estuary temperatures never were behind 10°C; chlorophyll *a* concentration was always high. These two factors should explain the *A. clausi* biological cycles features in the Mondego estuary.

Acknowlegements

The authors would like to express their gratitude to the Portuguese Foundation for Science and Technology for supporting this study through the PRAXIS XXI funding program.

References

Alcaraz, M., Coexistence and segregation of congeneric pelagic copepods: spatial distribution of the *Acartia* complex in the Ria of Vigo (NW Spain). J. Plankton Res., 5(6) (1983) 891–900.

Allen, K.R., Relation between production and biomass. J. Fisheries, Research Board Can., 28 (1971) 1573–1581.

Azeiteiro, U.M., Marques, J.C. and Ré, P., Zooplankton annual cycle in the Mondego river estuary (Portugal). Arquivos Museu Bocage, 3(8) (1999) 239–263.

Azeiteiro, U.M., Marques, J.C. and Ré, P., Zooplankton assemblages in a shallow seasonally tidal estuary in temperate Atlantic ocean (western Portugal: Mondego Estuary). Arquivos Museu Bocage 3(12) (2000) 357–376.

Bacelar-Nicolau, P., Nicolau, L.B., Morgado, F., Pastorinho, R., Marques, J.C. and Azeiteiro, U.M., Bacterioplankton dynamics in the Mondego estuary (Portugal). Acta Oecologica, 24 (2003) S67–S75.

Banse, K. and Mosher, S., Adult body mass and annual production/biomass relationships of field populations. Ecol. Monogr., 50 (1980) 355–379.

Bernard M., La production hivernale et printanièle du plankton à Alger. Premières observations, Rapp. Comm. Int. Expl. Sci. Mer Médit., 14 (1958) 3–196.

Billones, R.G., Tackx, M.L., Flachier, A.T., Zhu, L. and Daro, M.H., Image analysis as a tool for measuring particulate matter concentrations and gut content, body size, and clearance rates of estuarine copepods: validation and application. J. Mar. Syst., 22 (1999) 179–194.

Binet, D., Cycles biologiques et migrations ontogéniques chez quelques copepods pélagiques des eaux ivoiriennes. Cahiers ORSTOM Océanografie, Vol. 15(2) (1977) 111–138.

Bond, W.J., Keystone species, In: Shulze, D.E. and Mooney, H.A. (eds.), Biodiversity and Ecosystem Function, Springer-Verlag, Berlin, 1994, pp. 243–252.

Christou, E. and Verriopoulos, G., Length, weight and condition factor of *Acartia clausi* (Copepoda) in the eastern Mediterranean. J. Mar. Biol. Assoc. UK, 73 (1993) 343–353.

Conover, R.J., Oceanography of Long Island Sound 1952–1954. 6. Biology of *Acartia clausi* and *Acartia tonsa*, Bull. Bingh. Oceanography Coll., 15 (1956) 156–233.

Deevey, G.B., The annual cycle in quantity and composition of the zooplankton of the Sargasso Sea off Bermuda. Limnology Oceanography, 16(2) (1971) 1–44.

Digby, P.S.B., The biology of the small planktonic copepods of Plymouth. J. Mar. Biol. Assoc. UK, 29 (1950) 393–438.

Escaravage, V. and Soetaert, K., Secondary production of the brackish copepod communities and their contribution to the carbon fluxes in the Westerschelde estuary (The Netherlands). Hydrobiologia, 311 (1995) 103–114.

Feinberg, R.L. and Dam, H.G., Effects of diet on dimensions, density and sinking rates of fecal pellets of the copepod *Acartia tonsa*. Mar. Ecol. Progr. Ser., 175 (1998) 87–96.

Gaudy, R., Contribution a la connaissance du cycle biologique des copepods du Golfe de Marseille, 2. Étude du cycle biologique de quelques espèces caractéristiques. Tethys, 4 (1972) 175–242.

Greze, V.N. and Baldina E.P., Changements de population et production annuelle d'*Acartia clausi* et *Centropages kroyeri* dans la zone néritique de la Mer Noire (en Russe). Trudy Sevastopol. Boïl. St., 17 (1972) 149–161.

Heinle, D., Harris, R., Ustach, J. and Flemer, D., Detritus as food for estuarine copepods. Mar. Biol., 40 (1977) 341–353.

Hirst, A.G., Sheader, M. and Williams, J.A., Annual pattern of calanoid copepod abundance prossome length and minor role in pelagic carbon flux in the Solent, UK. Marine Ecol. Progr. Ser., 177 (1999) 133–146.

Irigoien, X. and Castel, J., Feeding rates and productivity of the copepod *Acartia bifilosa* in a highly turbid estuary; the Gironde (SW France). Hydrobiologia, 311 (1995) 115–125.

Jeffries, H., Berman, M., Poularikas, A., Katsinis, C. and Melas, I., Identification of zooplankton by pattern recognition. Mar. Biol., 78 (1998) 329–334.

Kennish, M.J. (ed.), Ecology of Estuaries. CRC Press, New York, 1990.

Klein, W.C.M. and Gonzalez, S.R., Influence of temperature and food concentration on body size, weight and lipid content of two calanoid copepod species. Hydrobiologia 167–168 (Dev. Hydrobiologia 47) (1988) 201–210.

Kleppel, G.S., Environmental regulation of feeding and egg production by *Acartia tonsa* off southern California. Mar. Biol., 112 (1992) 57–65.

Krylov, V.V., Relation between wet formalin weight of copepod and copepod body length. Oceanology, 8 (1968) 723–727.

Lee, W.Y. and McAlice, B.J., Seasonal succession and breeding cycles of three species of *Acartia* (Copepoda: Calanoida) in a Maine estuary. Estuaries, 2(4) (1979) 228–235.

Liang, D. and Uye, S., Population dynamics and production of the planktonic copepods in a euthrophic inlet of the Inland Sea of Japan, II, *Acartia omorii*. Mar. Biol., 125 (1996) 109–117.

Liang, D., Uye, S. and Onbé, T., Population dynamics and production of the planktonic copepods in a euthrophic inlet of the Inland Sea of Japan, I, *Centropages abdominalis*. Mar. Biol., 124 (1996) 527–536.

Mackas, D.L., Seasonal cycle of zooplankton of southwestern British Columbia. Can. J. Fisheries Aquatic Sci., 49 (1992) 903–921.

Morgado, F.M.R., Ecologia do zooplâncton da Ria de Aveiro. Caracterização Espacio-Temporal, Transporte Longitudinal e Dinâmica Tidal, Nictemeral e Lunar. Tese de Doutouramento, Universidade de Aveiro, 1997.

Omori, M. and Ikeda, T., Methods in Marine Zooplankton Ecology. Wiley-Interscience, New York, 1984.

Pardal, M. and Azeiteiro, U.M., Zooplankton biomass, abundance and diversity in a shelf area of Portugal, the Berlenga Marine Natural Reserve. Arquipélago, Life Mar. Sci., 18(A) (2001) 25–33.

Pastorinho, M.R., Vieira, L., Ré, P., Morgado, F., Pereira, M.J., Bacelar-Nicolau, P., Marques, J.C. and Azeiteiro, U.M., Population dynamics, biometry, production, histology and histochemistry of *Acartia tonsa* (Crustacea: Copepoda) in a temperate estuary (Mondego estuary, Western Portugal). Acta Oecologica, 24 (2003) S259–S273.

Pertsova, N.M., Average weights and size of abundant species of zooplankton in the White Sea. Oceanology, 7 (1966) 240–243.

Porumb, F.I., Contributions à l'étude de la reproduction, du développement et de la repartition des copepods pélagiques dans la zone néritique du littoral roumain de la Mer Noire (*Acartia clausi* Giesbr. et *Centropages kroyeri* Giesbr.). Travaux Mus. Hist. Naturele Grigore Antipa, 8 (1968) 243–250.

Razouls, C., Etude dynamique et variations saisonnières du plankton dans la région de Roscoff (première partie, les Copépodes). Cahiers Biologi Marin., 6(2) (1965) 219–254.

Sautour, B. and Castel, J., Comparative spring distribution of zooplankton in three macrotidal European estuaries. Hydrobiology, 311 (1995) 139–251.

Shmeleva, A.A., Weight characteristics of the zooplankton of the Adriatic sea. Bull. Inst. Oceanografie Monaco, 65(135) (1965).

Strickland, J.D. and Parsons, T.R., A practical handbook of seawater analysis. Bull. Fisheries Res. Bd. Can., 167 (1972) 1–311.

Tackx, M., Zhu, L., DeCoster, W., Billones, R. and Daro, M., Measuring selectivity of feeding by estuarine copepods using image analysis combined with microscopic and Coulter counting. ICES J. Mar. Sci., 52 (1995) 419–425.

Tchaianova L.A., Production et croissance des copepods pélagiques de la Mer Noire (en Russe). Trudy Karadag biology St., 10 (1950) 78–105.

Uye, S.I., Length-weight relationships of important zooplankton from the Inland Sea of Japan. J. Oceanography Soc., 38 (1982) 149–158.

Valiela, I., Marine Ecological Processes, 2nd ed., Springer, 1995.

Vieira, L., Ré, P., Morgado, F., Pereira, M.J., Marques, J.C.

and Azeiteiro, U.M., Population dynamics, biometry and production of *Acartia bifilosa* var. *inermis* (Crustacea: Copepoda) in a temperate estuary (Mondego estuary, Western Portugal). Arquivos Museu Bocage, Nova Série, 3(17) (2002) 423–442.

Vieira, L., Azeiteiro, U., Ré, P., Pastorinho, R., Marques, J.C. and Morgado, F., Zooplankton distribution in a temperate estuary (Mondego estuary southern arm: Western Portugal). Acta Oecologica, 24 (2003) S163–S173.

Vucetic, T., Zooplankton investigations in the Sea Water Lakes "Malo Jezero" and "Veliko jezero" on the Island of Mljet. Acta Adriatica, 6(4) (1957).

Williams, R., Conway, D. and Hunt, H., The role of copepods in the planctonic ecoystems of mixed and stratified waters of the European shelf seas. Hydrobiologia, 292/293 (1994) 521–530.