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DEPARTAMENTO DE CIÊNCIAS DA VIDA

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

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David Garrido Dinis

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Dissertação apresentada à Universidade de Coimbra para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Ecologia Aplicada, realizada sob a orientação científica do Professor Doutor Miguel Pardal (Universidade de Coimbra)

David Garrido Dinis

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Para o meu avô João.

Resumo

Os estuários são usados como zonas de viveiro para uma grande quantidade de espécies, estando sujeitos a constantes pressões antropogénicas e ambientais. O objectivo deste trabalho foi verificar em que medida os eventos climáticos extremos e factores de larga escala influenciam a população de *Crangon crangon* no estuário do rio Mondego.

A monitorização no estuário decorreu de Junho de 2003 a Julho de 2010 com uma periodicidade mensal até 2006 e posteriormente bimensal, com recurso a um arrasto de vara de 2 m, em cinco estações de amostragem ao longo do gradiente de salinidade.

Entre 2003 e 2010 existiram períodos de seca, períodos de chuva intensas e ondas de calor, que influenciaram as descargas de água doce no estuário, tendo sido considerados de seca extrema os anos de 2005, 2007 e 2008. Durante este período, foram observados picos de densidades de juvenis duas vezes por ano (verão e inverno). A população de *C. crangon* no estuário é essencialmente constituída por juvenis e indivíduos adultos até um ano e meio. Tendo em conta as densidades de *C. crangon*, os principais picos ocorreram na primavera e verão e maioritariamente no braço Norte do estuário, tendo sido o valor mais alto em Junho 2003 (134 indivíduos $1000m^{-2}$).

A produção secundária teve o seu valor mais elevado no ano de 2003/2004 (3.45 mg AFDW m^{-2} y^{-1}) e o valor mais baixo no ano de 2007/2008 (0.62 mg AFDW m^{-2} y^{-1}). Os valores da relação $P/\bar{B}$ obtidos foram mais baixos nas comparado com outras populações existentes mais a norte.

Apesar de não terem sido observadas alterações nos padrões de recrutamento e de produção secundária, foram observadas alterações espaciais no estuário, nomeadamente no local de fixação dos juvenis, visto estes serem os que apresentam maior capacidade de osmorregulação, conseguindo deslocar-se com mais facilidade no estuário até às zonas mais a montante.

Foi também observado que os juvenis são os mais susceptíveis aos factores ambientais de larga escala, nomeadamente a temperatura à superfície da mar (SST), o índice NAO, o escoamento e a intensidade vento na componente Norte-Sul. Em geral, a totalidade da população foi afectada apenas pelo vento Norte-Sul, um indicador de eventos de afloramento costeiro.

Com este estudo, podemos concluir que a espécie de *C. crangon,* ao contrário de outras espécies que vivem no estuário do Mondego, não sofreu alterações significativas tendo em conta os factores climáticos extremos que se verificaram durante o período em causa. No entanto, esta população, e nomeadamente os juvenis, são influenciados em certa medida pelos factores ambientais de larga escala, que condicionam o clima em Portugal continental.

Palavras-chave: *Crangon cragon*, eventos climáticos extremos, estuário do Mondego, respostas populacionais

Abstract

Estuaries are known for being nursery areas for a variety of species, however, being subject of anthropogenic and environmental pressures, as extreme weather events. The objective of this study was to assess how extreme weather events and long-scale factors influence *C. crangon* populations in the Mondego estuary.

The monitorization of the estuary was made from June 2003 to July 2010 with a monthly periocity until 2006 and after that bimonthly, by a 2m beam trawl with a tickler chain and 5mm mesh-size in the cod end, in five sampling stations along the salinity gradient.

Between 2003 and 2010 existed drought periods, heavy rain periods and heat waves, which influenced runoff on the estuary, and the years of 2005, 2007 and 2008 were considered extremely dry. During this period, it was observed density peaks of juveniles twice per year (summer and winter) being the total density in the estuary higher in spring and summer. The *C. crangon* population in the estuary is mainly composed by juveniles and adults up to one and an half years.

Secondary production presented its highest value in the year of 2003/2004 (3.45 mg AFDW m^{-2} y^{-1}) and the lowest in the year of 2007/2008 (0.62 mg AFDW m^{-2} y^{-1}). The $P/\bar{B}$ ratio obtained were lower compared to those obtained in other studies.

Despite not being observed modifications in the recruitment patterns and secondary production, some spatial alterations in the estuary were observed, mainly in the fixing spot of juveniles, as they were the ones with highest osmorregulation capacity, being able to dislocate to the stations more upstream.

It was also noticed that juveniles are more susceptible to long-scale environmental factors, mainly sea surface temperature (SST), NAO index, runoff and north-south wind intensity. In general the total population was affected by the north-south wind.

With this studie, we can conclude that *C. crangon*, unlike other species that live in the Mondego estuary, did not suffer any significant alteration taking into account the extreme weather events reported during the study period. However, this populations, and mainly juveniles, are influenced at least to some extent by environmental long-scale factors, that condition weather in continental Portugal.

Keywords: *Crangon cragon*, extreme weather events, Mondego estuary, population responses

Chapter 1

- General Introduction -

1. General Introduction

1.1. Estuaries

Known as transition areas connecting the river and the marine system, estuaries suffer permanent oscillations of temperature, oxygen, turbidity and salinity from the brackish waters of the upper reaches to the euhaline downstream areas. This salinity gradient combined with the normal typical hydrodynamic fluctuations of freshwater flow and seawater invasion are responsible for the distribution of the organisms in the estuary (Thiel *et al.*, 1995; Whitfield, 1999; Kimmerer, 2002; Leitão *et al.*, 2007). That is why natural variations like extreme weather events or man-made changes like dams or dredging activities have such a huge impact on the estuarine species (Kimmerer, 2002).

Due to their location, usually near big cities, the goods and services provided by estuaries such as the tourism, recreational areas, protection against floods, replenishment of coastal fisheries stocks, sediment and nutrient cycling, among others, makes the estuaries a valuable ecosystem. All these goods lead to intense human activity and as consequence the natural environmental suffers dramatic changes (de Jonge *et al*., 2002; Dauvin & Ruellet, 2009).

Another important characteristic of the estuaries is their role as nursery and shelter areas, providing to the juveniles stages of many species high food availability, favourable conditions for rapid growth and good survival and finding refuge from predators (Beck *et al*., 2001).

Estuaries also have high levels of production (primary and secondary), supporting a wide range of fishes and invertebrates (Beck *et al.*, 2001). Due to all these features estuaries are placed among the most productive (Kennish, 2002; McLusky & Elliott, 2004; Dolbeth *et al*., 2007) and heavily populated areas throughout the world (Nichols *et al.*, 1986).

1.2 Mondego estuary

The Mondego estuary (40º08'N, 8º50'W) is a small estuary of 8.6 km on the western coast of Portugal and a typical intertidal estuary (Lopes *et al*., 2000). It comprises two arms (north and south) with very different hydrologic features that separate at approximately 7 km from the shore and join again near the mouth, being divided by the Murraceira Island.

The North arm is deeper, with 5 to 10 m depth at high tide and tidal range of 2 to 3 m and constitutes the principal navigation channel and the location of the Figueira da Foz harbour. The south arm is shallower, with 2 to 4 m depth at high tide and tidal range of 2 to 3 m and it was silted up in the upstream areas until 2006. Since 2006, the reestablishment of the communication between the south and north arm led to an improvement in hydrodynamics and consequent reduction of the residence time in the south arm (Neto *et al*., 20). Nevertheless, freshwater flow is still carried mainly by the north arm. In the south arm the circulation also depends on tides and on the relatively small freshwater input, carried out through the Pranto River, a small tributary system, which is regulated by a sluice, according to the water needs in the surrounding rice fields. These characteristics make this arm particularly susceptible to eutrophication due to the organic enrichment and low hydrodynamics. In the south arm, about 75% of the total area consists of intertidal mudflats, while in the north arm they stand for less than 10% (Pardal *et al.*, 2000, 2004; Marques *et al*., 2003; Cardoso *et al.*, 2004).

Presently anthropogenic pressure affects the Mondego estuary in several ways. In the north arm there is the harbour and its maintenance and the regularization of the river channel led to a rapid degradation in the area. The northern arm receives the bulk of the discharge of the Mondego. The southern arm is mostly controlled by the small Pranto River and tidal action (Marques *et al*., 2007) suffering from raw sewage disposal and high nutrient inputs from agricultural and fish farms in the upstream areas. Combined with a high water residence time, this led to eutrophication processes, resulting in occasional spring macroalgae blooms of *Enteromorpha* spp. over the past two decades (*e.g*. Pardal *et al*., 2004; Dolbeth *et al*., 2007).

The Mondego estuary is an extensively studied system with published works on fauna and flora, for instance ichthyoplankton (Ligia *et al*., 2011), fish communities (Martinho *et al.*, 2007), estuarine production (Dolbeth *et al*., 2007), benthic food webs (Baeta *et al.,* 2011), planktonic communities (Cotrim *et al*., 2007), benthic species like *Hydrobia ulvae* or *Scobicularia plana* (Cardoso *et al*., 2008) and macroinvertebrates like *Carcinus maenas* (Bessa *et al*., 2010) and *Crangon crangon* (Viegas *et al*., 2007).

Figure 1 – Mondego River estuary.

1.3 Global changes and extreme weather events

Despite all the concern about global changing and the consequences of human impact in the environment, the emissions of greenhouse gases (GHG) had been increasing in the atmosphere between 1970 and 2004 (~80%), and the levels of carbon dioxide are at their highest level in at least 65,000 years and continue to rise. This accumulation of GHG in the atmosphere will lead to an increase of the global surface temperatures in about 1.1-6.4ºC by 2100 and to several others problems associated, as the ocean acidification, sea level rise, reduction in thickness and extent of glaciers, ice sheet and sea ice (IPCC, 2007).

As consequence extreme weather events will occur more often and with higher intensity (Easterling *et al.*, 2000; Alexander *et al.*, 2006; Houghton, 2009), floods will be more regular (Santos *et al.*, 2002), heat and cold waves more frequent. Portugal suffered three severe drought periods in the last ten years (2003, 2005 and 2006) (Portuguese Weather Institute; Santos *et al.*, 2002) having a strong impact on coastal ecosystems, meaning that the normal parameters of estuaries will change, provoking alterations on the reproduction and recruitment patterns of estuarine species (Cardoso *et al*., 2007; Chainho *et al*., 2007). There are some described cases of alteration in the Mondego estuary due the extreme events on the *H. ulvae*, by wiping out part of its population (Cardoso *et al*., 2008), decline on the macrobenthic communities, degradation of the estuary (Cardoso *et al*., 2008), decline on the recruitment of nursery species (Martinho *et al*., 2009) and compromises the restoration of the estuary (Grilo *et al*., 2011).

1.4. Brown shrimp *Crangon crangon*

Crangon crangon (Linnaeus, 1758) belongs to the Decapoda order and Crangonidae family. It has a wide distribution range along the Europe coast from the White Sea in the north Russia to the Mediterranean and Black Seas (Tiews, 1970; Gelin *et al.*, 2000). It is present in Malta (Micaleff & Evans, 1968) and Morocco (Campos & Van der Veer, 2008), within the latitude parallels of 34°N and 67°N (Mediterranean, temperate and cold climatic zones).

It has an important role on near-shore ecosystems for being a highly abundant prey (Nehls & Tiedemann, 1993; Hampel *et al.*, 2005) as well as a predator (Norkko, 1998; Hiddink *et al*., 2002; Wennhage, 2002). As a prey it plays an important role to some juveniles and adult fishes (McLusky & Elliot, 2004). On the Mondego estuary *C. crangon* is predated by several species with relevant economic value as *Platichthys flesus*, *Solea solea* and *Dicentrarchus* *labrax* (Martinho, 2005) and is also an important benthic predator of other species (Phil & Rosenberg, 1984; Beukema, 1992; Oh *et al*., 2001).

This species is commercially exploited and consequently it has been intensively studied in terms of abundance and stock (Phil & Rosenberg, 1982; Spaargaren, 2000; Siegal *et al.*, 2005), fisheries by-catch and discards (Berghahan *et al.*, 1992; Berghahn & Purps, 1998; Gamito & Cabral, 2003) and migratory behavior (Hartsuyker, 1966; Boddeke, 1976; Janssen & Kuipers, 1980). *C. crangon* is caught in estuaries and inshore areas of the countries bordering the North Sea and has a market value between €50-70 million per year (Polet, 2002; Anon, 2006). Along the years there have been some oscillations in terms of landings but its highest catch occurred in 2006 – 37,000t (Innes & Pascoe, 2007). In 1997 the estimate earnings were about 98.2 million euros (Pascoe & Revill, 2004), and in 2006 about 91.3 million euros (Innes & Pascoe, 2007).

1.5. Life cycle

The reproduction occurs in more saline waters offshore, usually in sandy or muddy areas in a depth between 10-20m (Tiews, 1954; Henderson & Holmes, 1987. The reproduction occurs almost continuously throughout the year, with main spawning seasons in spring/summer (Viegas *et al.,* 2007). The growth is irregular due the rigid exoskeleton and therefore presents several moultings (Smaldon *et al.*, 1993). After the hatch of the eggs, a free-floating planktonic larval stage migrates to coastal waters (van Donk & De Wild, 1981) developing into benthic post-larvae that invade estuaries and shallow waters, where they find abundant sources of food and grow (Tiews, 1970; Boddeke *et* *al*., 1976; Beukema, 1992). After six months in the estuary they start to be reproductive active (Viegas *et al*., 2007), becoming adults and move to deeper waters, where they reproduce.

1.6. Main objectives

Climate changes are expected to affect ecosystems in many ways and it is essential to understand and predict the ecosystems' responses to this new source of stress. Taking this into account, the main objectives of this study were to provide information on how climate changes, and consequently the extreme weather events, will affect the *C. crangon* population in the Mondego estuary and compare and extrapolate these changes to other ecosystems. Another goal was to know with more detail which factors among the hydrological features, namely coastal wind speed and direction, currents, salinity, turbidity, water temperature precipitation and large ocean-atmosphere patterns such as the North Atlantic Oscillation (NAO), have significant influence on the reproduction, settlement, recruitment patterns and distribution of *C. crangon*.

Chapter 2

- Materials and methods -

2. Materials and methods

2.1. Sampling procedures and data acquisition

Sampling was performed at five stations ranging from marine to freshwater environments (Fig.2). Surveys took place monthly or every two months from June 2003 to July 2010 (with exception for September-October 2004 and October-December 2008, due to technical constraints). Samplings were made during the night, at high tide of spring tides due to better gear efficiency.

The gear used was a 2 meters beam trawl with one tickler chain and 5 mm mesh size in the cod end. Three trawls were towed at each station for a mean of 5 minutes each, covering at least an area of 500m^2. Bottom water was analyzed for salinity, temperature, pH and dissolved oxygen.

Hydrological data was obtained from INAG – Portuguese Water Institute (*http://snirh.inag.pt*). Both monthly precipitation (from Jane 2003 to July 2010) and long-term monthly average precipitation (from 1961 to 1991) was obtained from the Soure 13F/01G station. Freshwater runoff was acquired from INAG - Portuguese Water Institute (*http://snirh.inag.pt*) station Açude Ponte Coimbra 12G/01A, near the city of Coimbra (located 40 km upstream).

North Atlantic Oscillation (NAO) Index (given by the pressure difference between Lisbon (Portugal) and Reykjavik (Iceland) data was supplied by NOAA/National Weather Service – Climate Prediction Center (*http://www.cdc.noaa.gov*). Sea surface temperature (SST), wind data, both north-south and east-west components, were acquired from the International Comprehensive Ocean Atmosphere Data Set (ICOADS) online database (*http://dss.ucar.edu/pub/coads*, Slutz *et al.*, 1985) concerning the 1º Lat x 1º Long square nearest to the Mondego estuary.

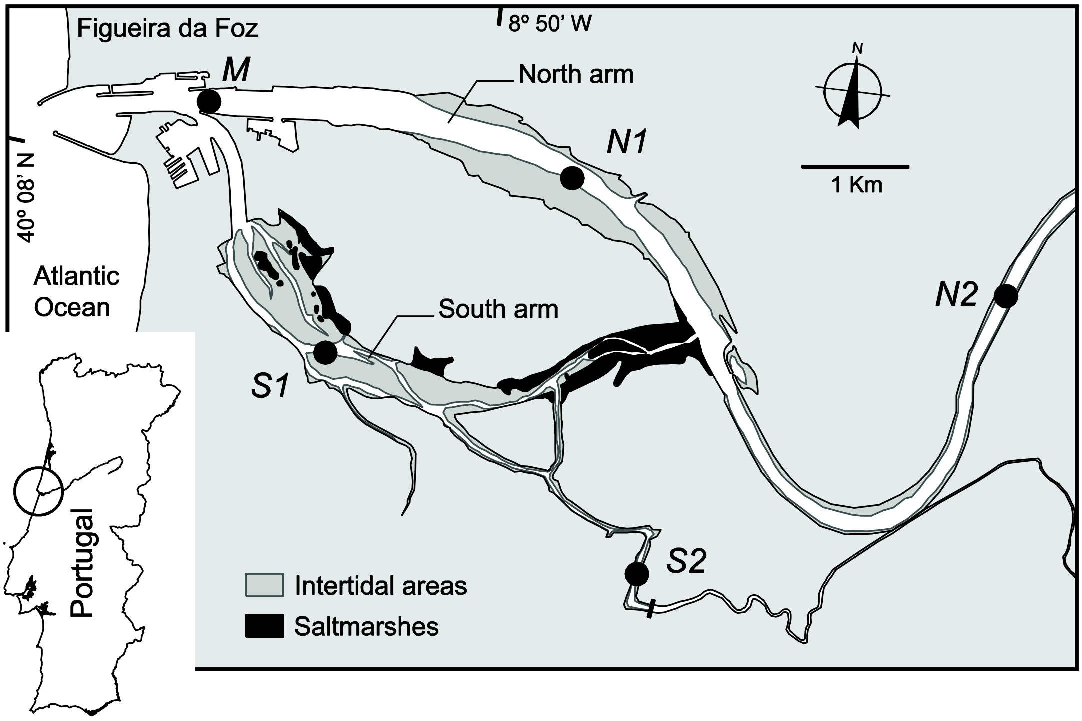


Figure 2 – Location of the five sampling stations in the Mondego estuary (M, N1, N2, S1 and S2).

2.2. Sample analysis

After sampling the shrimps were frozen and stored. Before analysis, shrimps were unfrozen and preserved in 4% formaldehyde for 24 hours and then transferred to 70% ethanol for long-term storage.

Carapace length (CL) was measured as the shortest distance between the posterior margin of the orbit and the mid-dorsal posterior edge of the carapace (to the nearest 0.01 mm using a binocular micrometer). The total length (TL) was measured similarly from the posterior margin of the orbit to the tip of the telson. A regression between the CL and the TL was also used (Viegas *et al*., 2007):

TL = 4.7906*CL-1.1295 (r^2=0.98, N=702)

To determinate the sex three different morphological characteristics were observed: the size and shape of the endopodite of the first pleopod and the presence or absence of the *appendix maculina*. Shrimps with CL<3.5mm were considered immature.

2.3. Data analysis

The population structure was defined by tracking recognizable cohorts from successive sampling dates. Spatial samples were pooled together and analyzed through size frequency distribution of successive sampling dates and cohorts determined using FAO-ICLARM Stock Assessment Tools (FiSAT software, provided in *http://www.fao.org/fi/statist/fisoft/fisat/index.html*). The cohorts were identified using Bhattacharya's and NORMSEP procedure, which provided the mean length, standard deviation, population sizes and separation indices for the identified age groups (Gayanilo *et al.*, 2005).

After recognition of the cohorts, the annual production was estimated with the cohort increment summation method (Winberg, 1971), according to:

$$P_{cn} = \sum_{t=o}^{T-1} \left(\frac{N_t + N_{t+1}}{2}\right) \times (\overline{w}_{t+1} - \overline{w}_t)$$

where P_{cn} is the growth production (g WW m^{-2} y^{-1}) of cohort n; N is the density (ind m^{-2}); $\overline{w}$ is the mean individual weight (g WW m^{-2}); t and t+1, are consecutive sampling dates. Population production estimates correspond to the sum of each cohort production (P_{cn}). Negative production values were not accounted for the overall shrimps estimates, which were regarded as no production.

The mean annual biomass ($\bar{B}$) was estimated according to:

$$\bar{B} = \left(\frac{1}{T}\right) \times \sum_{n=1}^{N_c} (\bar{B}_{cn}\, t_{cn})$$

where T is the period of study, which is always 365 days (yearly cycles) as the mean annual biomass is being computed; N_c is the number of cohorts found in the study period; B_{cn} is the mean biomass (g WW m^{-2}) of cohort n; t_{cn} is the time period of the cohort n (days), from the first appearance of individuals until they disappeared.

The environmental data (precipitation, runoff, sea surface temperature, estuarine temperature and salinity) was analyzed with Primer, with Principal Components Analysis (PCA) after data normalized.

The shrimp population was analysed according to two distinct periods: non-drought years and drought years, defined by reports of the Portuguese Weather Institute (Portuguese Weather Institute 2010, *www.meteo.pt*) and explored through PCA. The population density was divided into juveniles (individuals $\leq$ 3.5 mm of CL) males, females and ovigerous females. This data was explored using 2-way ANOSIM (from PRIMER routines) for the factors season and year. This allowed to check if there were differences in the density patterns for drought and non-drought periods. Previously, similarities in the density data were calculated as the Bray-Curtis coefficient after square-root-transformation of the raw data to scale down the scores of the most abundant groups (Clarke & Warwick, 2001).

The inter-annual relationship between the densities (juveniles and total density) and the environmental patterns (predictors) were analyzed with a Generalized Linear Model (GLM) in R software (R Development Core Team, 2008), where the number of shrimps is related to the environmental parameters. The GLM was built with an additive methodology: environmental parameters were tested independently for significance and subsequently, significant parameters were added to determine the residual deviance, the percentage explained by each parameter and the total percentage of the deviance explained. Juvenile and total densities (the response variables) were modelled as a function of salinity, runoff, precipitation, sea surface temperature, the North Atlantic Oscillation, dissolved oxygen, wind north-south and wind east-west. The final model was fitted only with the significant variables. For all the variables, three distinct scenarios were tested, to the juveniles and to all the population: one scenario with the parameters values matching with the density months, other scenario the parameters are one months prior of the corresponding month of density and a third one were the parameters are two months prior, since, according the biology of the specie, the oceanic/atmospheric factors can have a delay influence on the estuarine colonization, mainly on juveniles and larvae, to the overall population, intrinsic factors like salinity, temperature, runoff and wind can affect their abundance and distribution. This approach has already been applied to the fish community in the estuary (Martinho *et al.*, 2007). A significance level of 0.05 was used in all test procedures.

Chapter 3

- RESULTS -

3. Results

3.1. Environment analysis

The study period of seven-years revealed some atypical modifications on the estuary. Several years of drought with reduced precipitation originated a significant reduction in freshwater runoff into the estuary (Fig. 4). The hydrologic years of 2003, 2006 and 2009 were considered as regular, while 2004, 2005, 2007 and 2008 (Fig. 3) were extremely dry years, being the hydrologic year 2004 (from June 2004 to May 2005) the one with the lowest values of precipitation (422.6 mm against 892.2 mm for 1961–1991 mean, classified as the worst drought since 1931 by the Portuguese Weather Institute). In autumn, 2006 the levels of precipitation were high, making the salinity levels drop to the lowest levels during the study period (salinity value: 0) (Fig. 5), and the highest levels of salinity were in 2007 and 2009, making the station more upstream with almost the same value of salinity than the station M downstream (23 and 33 respectively).

Some heat waves occurred (Portuguese Weather Institute) in 2003, 2005 and 2009, being 2005 the driest year and the spring of 2009 the driest season since 1931, affecting the average water temperature on the estuary (the highest range of average water temperature was 8.8ºC in January and 22.7ºC in July, in 2005) and salinity (period of dry from March to October 2009). 2007 was the year with the second lowest annual precipitation in the last 60 years (Portuguese Weather Institute).

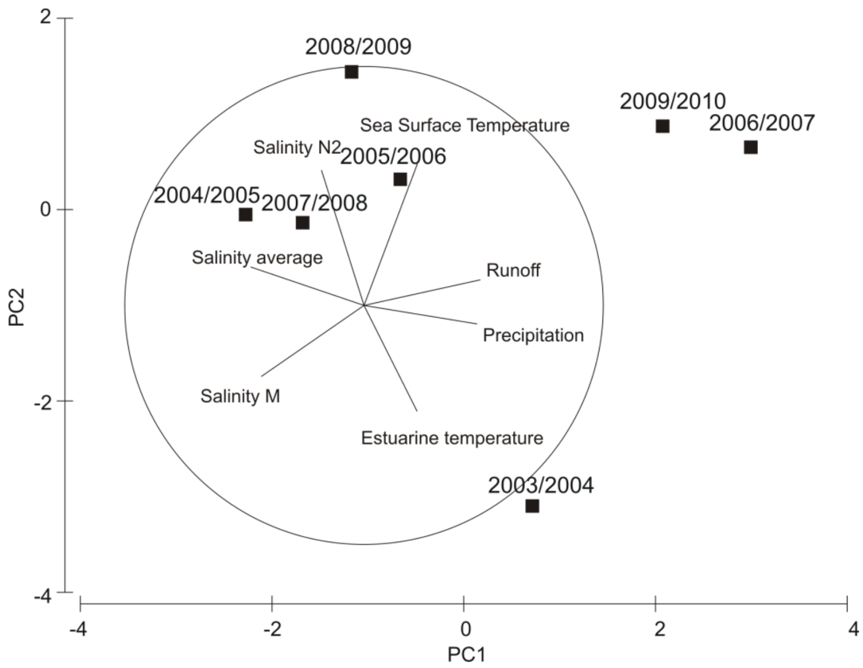


Figure 3 – PCA with the environmental parameters along the study period organized per year

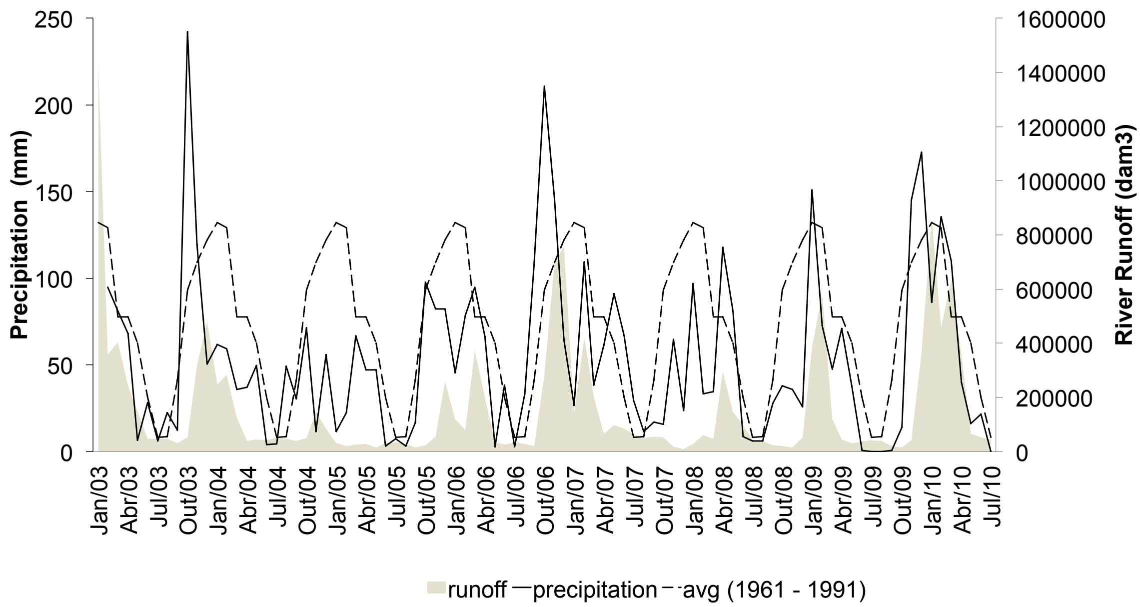


Figure 4 – Long-term variation of precipitation and river runoff in the Mondego River basin.

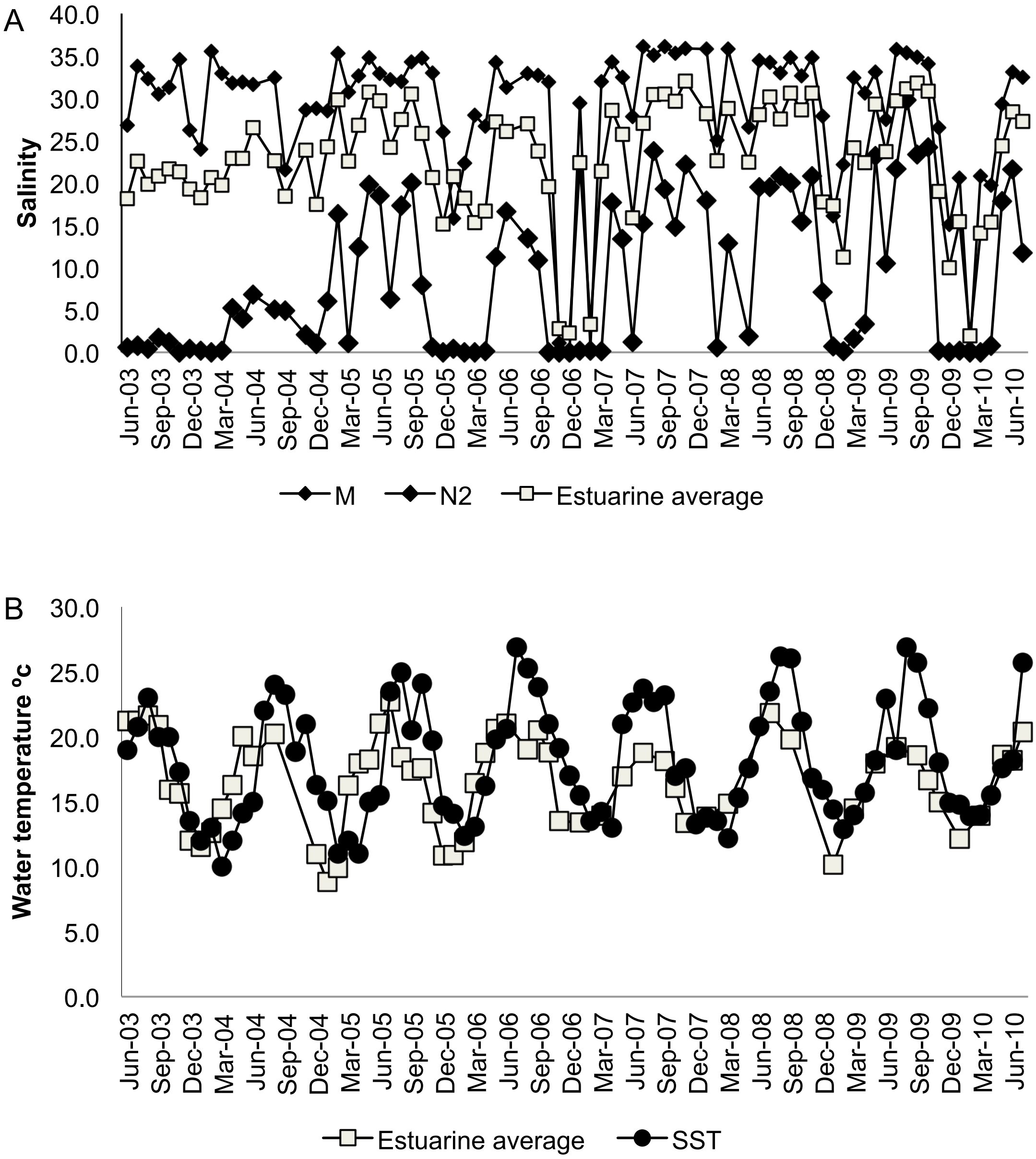


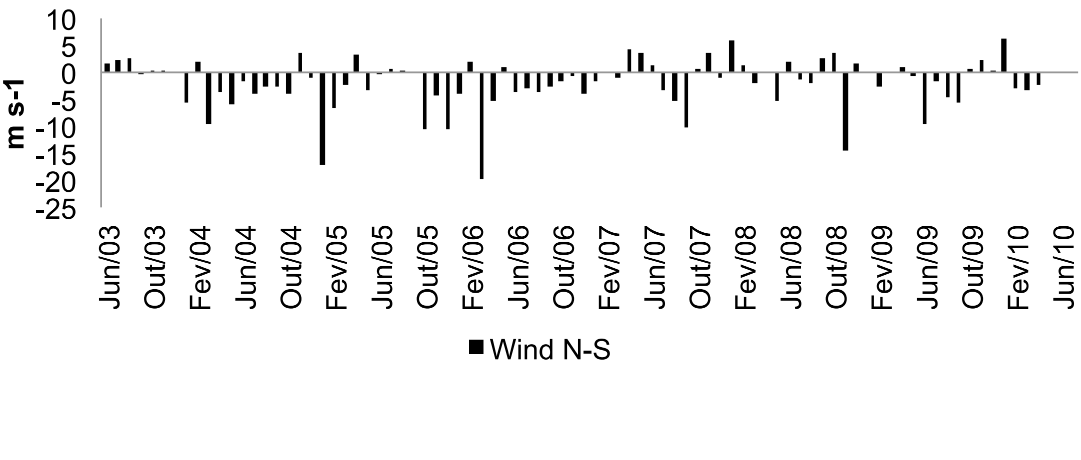
Figure 5 – Monthly variation of salinity at stations M (most downstream station), N2 (most upstream station) and estuarine average salinity values (A); and estuarine average temperature and sea surface temperature (SST) for the 1º Lat x 1º Long nearest to the Mondego estuary (B).

The Sea Surface Temperature (SST) ranged from 10ºC to 23.5ºC, with the lowest value in March 2004 and the highest value in August 2006 (Fig. 5).

Considering north-south wind, the average values were negative in all years (hydrologic year, from June to May) during the study period, which contributed to the occurrence of upwelling, being the months of January 2005, March 2006 and November 2008 with the most intensive wind from north to south with values of -17 m s^{-1}, -19.8 m s^{-1} and -14.5 m s^{-1} respectively. The year of 2005 had the lowest value (-4.23 m s^{-1}) and the year of 2008 the nearest zero value (-0.89 m s^{-1}).

The NAO index reveal to be more near to null values, however almost all years had negative values between -0.93 and -0.041 except the year of 2003/2004 that had a positive value (0,18) (Fig. 6) The variation along the years had been from -2.24 in October 2006 and 1.68 in May 2009.

A



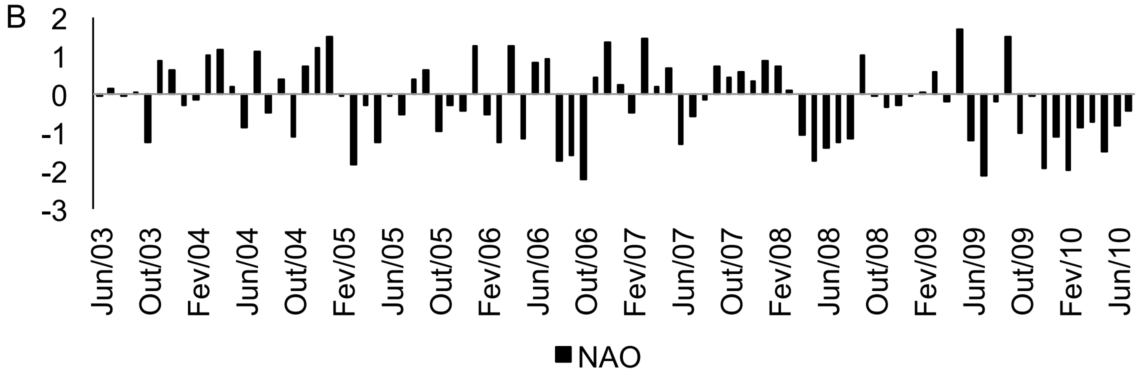


Figure 6 – Environmental variables Wind north-south (A) and North Atlantic oscillation index (B).

After knowing that there were no significant differences among the hydrologic years (two-way Anosim R=0,164, $p<0.001$), the factors responsible for the variations on population densities were assessed.

Among all the parameters tested to see if had some significance to explain the distribution and recruitment of *C. crangon,* the ones that explain some part of it are the Runoff, Wind north-south, sea surface temperature (SST) and the North Atlantic Index (NAO). However they do not have the same impact among all the population, some of them are significant for juveniles during recruitment and others to the population in general.

The data was organized by the parameters corresponding to two months earlier, one month earlier and the corresponding month of the changes.

Table I – Analysis of deviance table for the gamma-based GLM fitted to the total densities and juveniles densities (Res. Dev. – Residual deviance; % Expl. – Percentage of the deviance explained by the model).

	Parameters	Date of environmental parameters	p-value	Res. Dev.	Deviance	% Exp.
Densities of Juveniles	Runoff	same month	0.00629	24.11	36.13	33.27
	Wind N-S	same month	0.04239	26.52	36.13	26.61
	SST	1 month prior	0.0431	27.842	36.13	22.94
	SST	2 months prior	0.0319	27.629	36.13	23.53
	NAO	2 months prior	0.00238	24.287	36.13	32.78
Total Dens.	Wind N-S	same month	0.036	12.47	14.63	14.77

Considering the juvenile population, the runoff explained 33.27% of the densities, highest runoff, biggest are the densities of juveniles in the estuary, and with the wind north-sout explained 26.61% of the density, telling that values nearest zero are the best to recruitment (Table 1; Fig. 7). The SST explained 22.94% and the increases in temperature were beneficial to the juveniles densities (at least to some extent) (Fig. 8 and 9). The NAO index showed that negative values are more favourable to the juveniles (Fig.9), and explained 32.78%. To the general population only the wind north-south had a significant influence explaining 14.77% of the density (Fig.10).

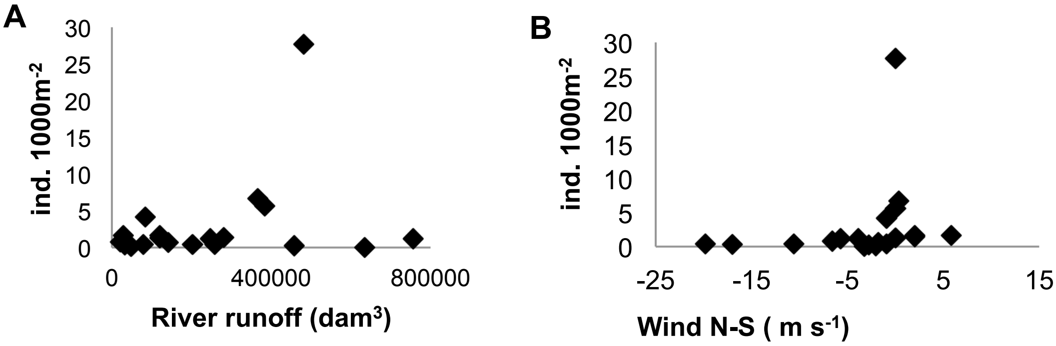


Figure 7 – Abundance of juveniles *C. crangon* (Ind. 1000 m^{-2}) in relation with (A) river runoff (dam^3), (B) wind N–S component (m s^{-1}) concerning the month of the densities values.

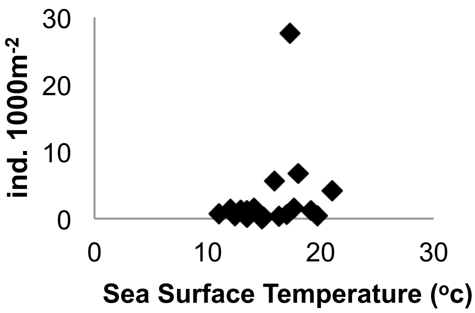


Figure 8 – Abundance of juveniles *C. crangon* (Ind. 1000 m^{-2}) in relation with sea surface temperature (ºC) concerning one month prior of the densities values.

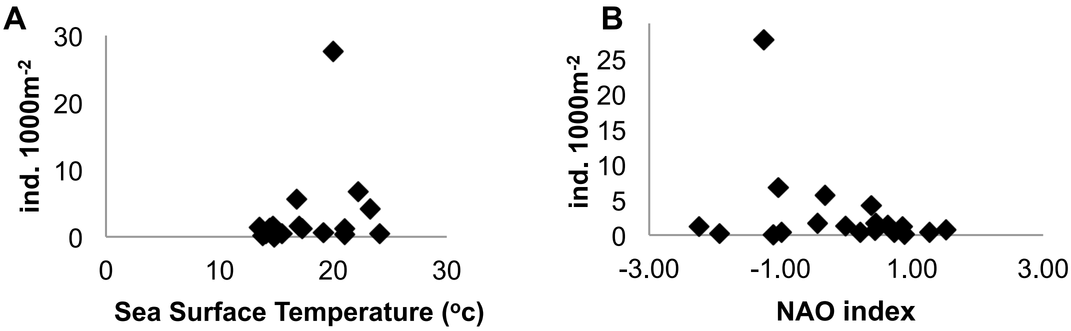


Figure 9 – Abundance of juveniles *C. crangon* (Ind. 1000 m^{-2}) in relation with (A) sea surface temperature (ºC), (B) NAO index concerning two month prior of the densities values.

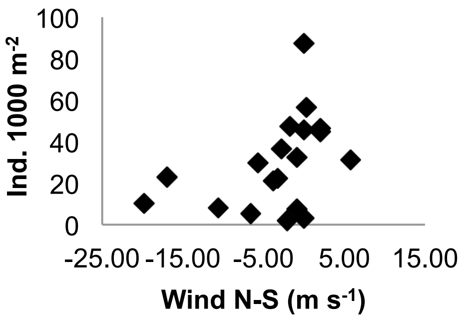


Figure 10 – Abundance of *C. crangon* (Ind. 1000 m^{-2}) in relation with wind N–S component (m s^{-1}) concerning the month of the densities values.

3.2. Population structure

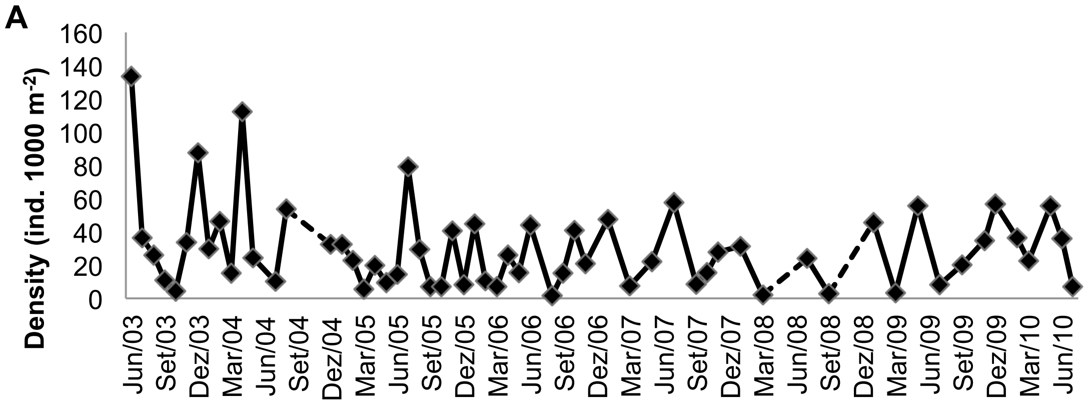
3.2.1. General data

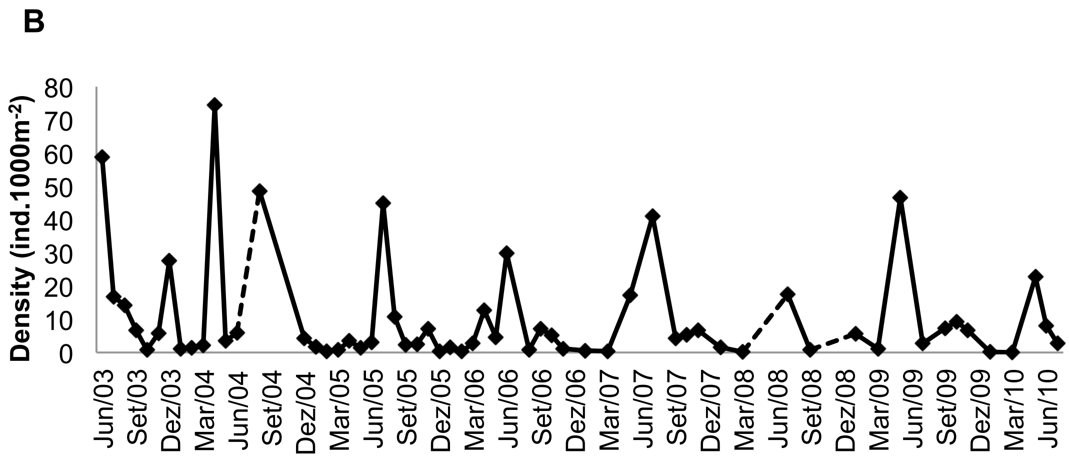
During the study were caught a total of 21417 individuals, 8011 of them were juveniles, 5098 males, and 8308 females (405 berried females). Most of them were caught on the stations M and N2 (43.5% and 28.4% respectively. The smaller juveniles, corresponding to the post-larvae stage, had 1.23mm CL (5mm TL), the biggest one was a female with 15.00mm CL (70.7mm TL) caught on February 2010, and the biggest male had 9.14mm CL (42.6mm TL) caught on November 2009.

3.2.2. Abundance and secondary production

C. crangon reached higher densities mainly on the spring and summer, presenting highest values in June 2003, April 2004 and July 2005 (134, 112 and 79 individuals per 1000m^{-2}, respectively), staying the rest of the study period more constant in about approximately 50 individuals per 1000m^{-2} with two peaks per year, in spring and summer. The north arm was the most responsible for these density peaks (Fig. 11).

The secondary production (Fig. 11) had peaks more defined than the density peaks, occurring mainly in winter (December) and summer (July) however there were some peaks in spring too (April and May), matching with the juvenile peaks.





C

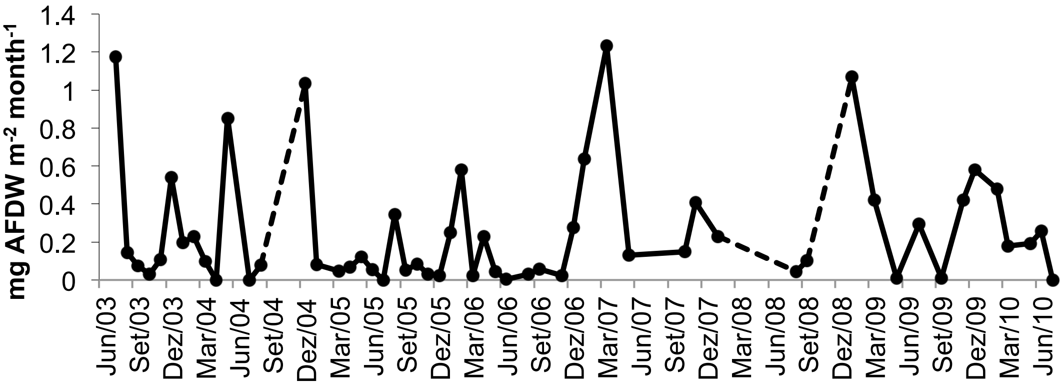


Figure 11 – Density variation (A), juveniles' density variation (B) and secondary production (C), in the estuary.

3.2.3. Population dynamics

The number of juveniles was higher in the stations of the north arm, having the biggest percentage on the M station (35% of all the juveniles along the study period). However there were some exceptions, for example in 2005 there were more juveniles on the station N2, and after June 2007 the number of juveniles were almost the same on both north arm stations, being the main influence on the densities observed in the estuary during the reproduction season. There are two peaks of juveniles per year, one bigger on the summer and other with smaller values in the winter (Fig. 12).

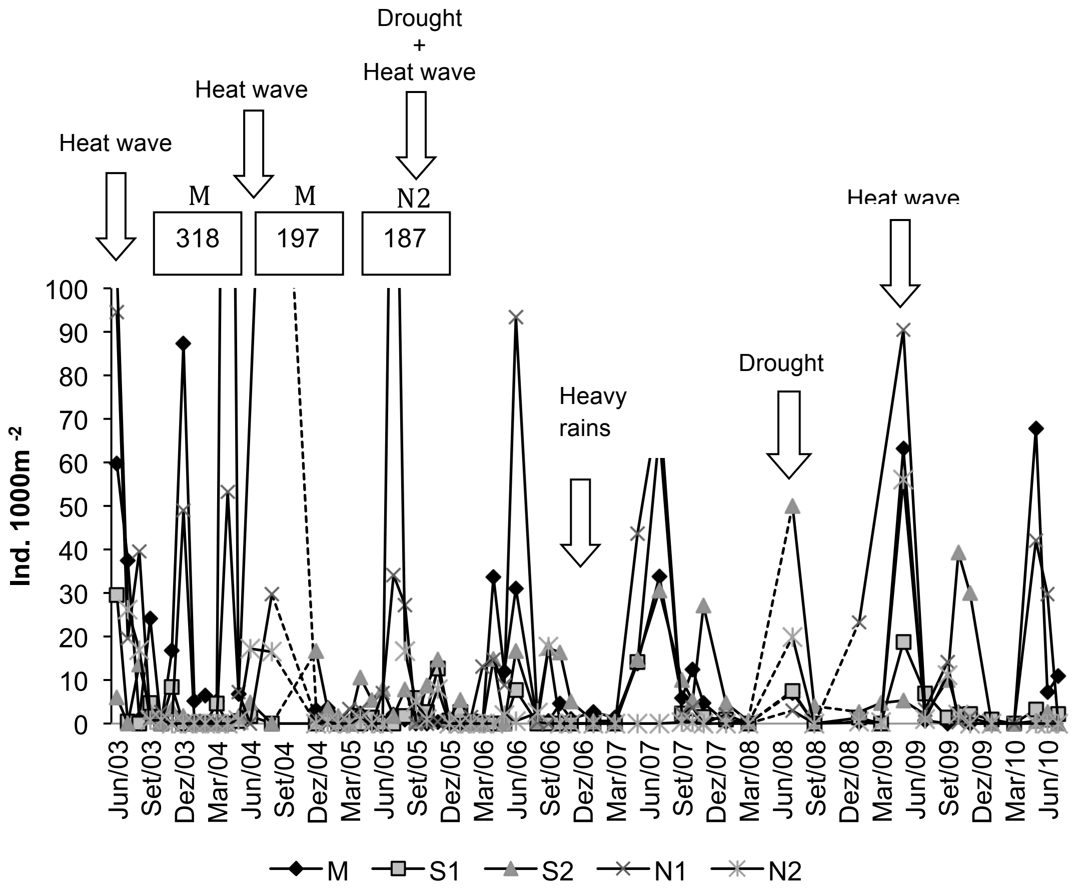


Figure 12 – Number of juveniles (CL < 3.5 mm) per 1000 m^2 on the five sampling station along the study.

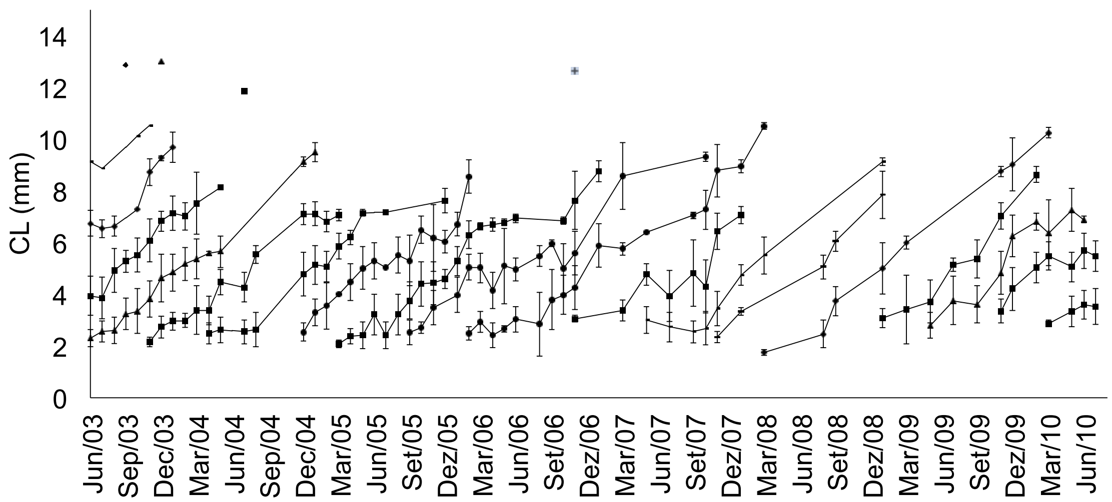


Figure 13 – *Crangon crangon* estimated growth for each cohort (all sampling stations combined) during the study period.

The appearance of juveniles in the estuary were mainly twice per year, one on the months of November and December and another on February, March and April (Fig. 13). This appearance is usually few months before the density peaks. They grow on the estuary during two years into the size of approximate 10mm CL, however there are some rare cases of adults that get into the estuary, having a CL around 13mm not making parte the normal population in the estuary.

The growth rate is almost the same between the two periods of recruitment, having the individuals of the cohorts of Autumn-Winter 6.45mm CL $\pm$0.37(29.8mm TL) after one year and the individuals of the spring cohorts 6.21mm CL $\pm$0.23 (28.6mm TL). The maturations (CL $\geq$3.5mm) occur after six months in the estuary.

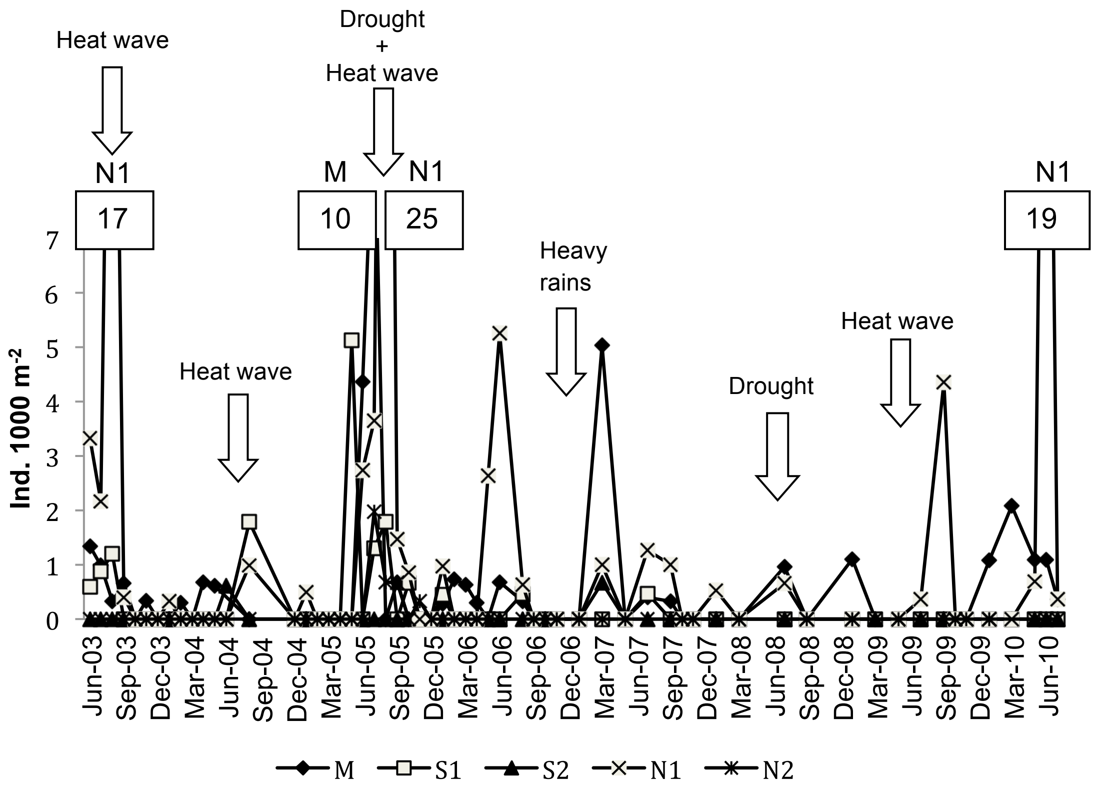


Figure 14 – Number of berried females per 1000 m^2 on the five sampling station along the study.

The berried females had some peaks of density (Fig. 14), mainly on the months with higher temperature. There were five peaks on the station N1 on the months of June and July of the year's 2003, 2005, 2006, 2009 and 2010, two on the station S1 in July 2004 and May 2005, and during the cold months they stay on the station M, on March 2007 January 2008 and February 2009.

Table II – Year variation of production (P), biomass (B) and P/$\bar{B}$ ratio along the seven years of the study period, for the *C. crangon*, and corresponding weather events.

hydrologic year	P (mg AFDW m^{-2} y^{-1})	B (mg AFDW m^{-2} y^{-1})	P/B (mg AFDW m^{-2} y^{-1})	weather event
2003/2004	3.45	0.85	4.08	Regular
2004/2005	1.43	0.27	5.29	Drought
2005/2006	1.72	0.49	3.48	Drought + Heat wave
2006/2007	2.39	0.65	3.70	Regular
2007/2008	0.62	0.22	2.83	Drought
2008/2009	1.65	0.28	5.93	Drought
2009/2010	2.15	0.56	3.82	Regular

The annual secondary production (P) of the population of *C. crangon* was estimated with values between 3.45 mg AFDW m^{-2} $year^{-1}$ in 2003/2004 and 0.62 mg AFDW m^{-2} $year^{-1}$ in 2007/2008. The annual biomass ($\bar{B}$) had values between 0.85 and 0.22 mg AFDW m^{-2} $year^{-1}$ giving a relation P/$\bar{B}$ of 3.4 and 0.62.

Chapter 4

- Discussion -

4. Discussion

4.1. Extreme weather events on coastal systems

Costal ecosystems are subjected to several anthropogenic stressors and usually they interact with each other, having an impact on biodiversity and ecosystem function (Vinebrooke *et al*., 2004; Dolbeth *et al*., 2007). Besides loading impacts such as eutrophication and more recently the recovery phase of the Mondego estuary, this estuary has been suffering the effect of extreme weather events that occurred with more frequency and intensity during the last decade. The drought periods have a huge impact on the aquatic system by reducing the flow of freshwater in the estuaries (Tallaksen *et al*., 1997).

C. crangon unlike other species on the Mondego estuary like the *Solea lascaris* (Martinho *et al*., 2007), *Hydrobia ulvae* (Cardoso *et al*., 2008), *Scobicularia plana* (Cardoso *et al*., 2008) and *Carcinus maenas* (Bessa *et al*., 2010) did not seem to have suffered any significant alteration along the study period, having just some spatial adjustments. It is known that *C. crangon* can live in temperatures between 6 and 30ºC (Abbott & Perkins 1977; Jeffery & Revill 2002, Freitas *et al*., 2007), and in the study period it was only observed minimum and maximum temperatures of 8.8ºC and 22.7ºC, respectively. However, the salinity levels directly affect the temperature tolerance of *C. crangon* (at low temperatures shrimps prefer high salinities, while at high temperatures, low salinities are preferred) (Broekema, 1942). Nevertheless, the mean salinity levels during the study period were never higher than 32 and lower than 10.

4.2. Densities

Densities varied along the period of study and presented peaks of juveniles in October, November and December and in February, March and April, which can be related to salinity values inside the estuary. Larvae are polyhaline (Criales & Anger, 1986), which can suggest that they develop during the months with low precipitation (therefore high salinity), which are the months previous to the ones where cohorts appeared. As they take few months to enter the estuary (Campos & Van der Veer, 2008), they start to appear in autumn and winter months, as shown by the results.

In general, adult shrimps maintain constant densities in the estuary (approximately 60 individuals per 1000 m^2) along the years, however there are some tendencies of placement within the estuary and some factors that can explain a part of our density observations. It is known that there are important factors that influence the recruitment of the juveniles such as the runoff, wind north-south, sea surface temperature and the NAO index. However they have a response on different times of the recruitment. Our observations indicate that the SST and the NAO index influences the recruitment in an earlier stage and the runoff and the wind north-south more directly. It is unclear if the larvae are transported passively (Rijnsdorp *et al*., 1985) or if they are able to affect this transport selectively (called selective tidal transport, as observed in flatfish species) by swimming up from the seabed during flood tides and remaining on the seabed during ebb tides (Rijnsdorp *et al*., 1985; Jager 1999). The results indicate that they can have a selective transport.

4.3. Population distribution and dynamics

The distribution of the specie along the estuary was according to the different environmental characteristics of each station, being the principal characteristics: temperature (Beukema 1979; Spaargaren 1980; Henderson & Holmes 1987), salinity (Tiews 1970; Labat 1977a, b; Marques 1982; Henderson & Holmes 1987; Gelin *et al*., 2001a, b), light intensity/day length (Spaargaren, 2000) and food conditions (Tiews, 1970; Boddeke, 1976; Spaargaren, 2000). By affecting the physiological performance of shrimps, this parameters are also responsible for the migration patterns, both tidally (Janssen & Kuipers, 1980), daily (Hartsuyker, 1966) and seasonally.

The juveniles, males, females and berried females have different ranges of optimal levels of salinity, temperature and O_2. Males are less capable of osmorregulating and thus tolerating lower levels of salinity (Lloyd & Yonge, 1947). Due to that, they do not get to the station more upstream (N2).

The juveniles seem to prefer lower salinities than adults (Marques, 1982). They swim upstream were the competition is lower and the environment is more favourable. The juveniles had their main distribution in stations M and N1, although when extreme weather events occur this distribution changed and juveniles appear in other stations, such as N2 (July 2005). This can be explained by the fact that when these events occur, the stations M and N1 are overpopulated by adult males and females, so juveniles migrate upstream, where they find better conditions (*i.e.* food availability, shelter, low predation), although the percentage on the most upstream station (N2) of juveniles is not too big. Around 10% of juveniles per year, except in 2004/2005 and in 2008/2009 when the percentage were higher on the station N2 (47% and 20%, respectively), having this higher percentages just when the conditions are favourable, in this case droughts.

The females are more sensitive to the temperature and salinity preferring high salinity when the temperature is lower and lower salinity when the temperature is high (Broekema, 1942). So, when temperature was lower the density on the station M was higher and when the temperature was higher they moved to the station S2.

Considering the berried females, salinity is the main factor affecting its distribution. July of 2005 was the month when highest numbers of berried females were present in the estuary. This was due to the preference of berried females for high salinity and after these extreme weather events, the salinity in estuary increased. This pattern was also found in August, 2003, June 2006, March 2007, September 2009 and July 2010, all months when extreme weather events occurred, increasing the salinity in the estuary.

4.4. Parameters that influence the *C. crangon.* Reproduction, settlement and recruitment

From the GLM analysis, SST, NAO, river runoff and the north-south wind component were the parameters (predictors) that significantly influenced the inter-annual peak abundance patterns of juvenile populations. Other environmental parameters that may influence this species' abundance, such as salinity or dissolved oxygen were not considered significant. Taking into account the species' biology, which include the migration of newly hatched larvae from coastal areas to estuaries, three distinct scenarios were evaluated: the direct response to the environmental parameters, and with a time lag of one and two months between the environmental parameters and the observed densities of juveniles and the total population.

SST was one of the most important predictors explaining the catches of *C. crangon* juveniles, when considering a time lag of one and two months. Although the total percentage explained was somewhat low, a general trend could be observed, in which higher SST values corresponded to higher densities. In fact, temperature is an important factor to the settlement of juveniles, and it seems that 25ºC is the optimal temperature to their growth (high limit is about 30ºC) (Freitas *et al*., 2007; Campos & Van der Veer, 2008).

The temperature has an important role on the life cycle of the *C. Crangon*: in his growth (Tiews 1954), incubation eggs period (Boddeke & Becker, 1979), time to sexually maturity (Meredith 1952), the timing of immigration and settlement of shrimp larvae (Beukema 1992) and also affects the salinity tolerance.

The NAO is a large-scale oceanographic process that influences the general climate patterns over the North Atlantic Ocean, North America and Europe, such as wind speed and direction, air temperature, sea surface temperature and rainfall (Hurrel *et al*., 2003). The negative phase of the NAO generally induces wet weather in southern Europe and dry weather in northern Europe, while a positive phase induces an opposite pattern. In addition, the NAO has been correlated with a range of ecological processes, such as fish stocks and landings (Attrill & Power, 2002; Teixeira *et al*., 2009). On the Portuguese coast, the NAO has been determined to influence not only the sea surface temperature (SST), but also the wind and current patterns (Henriques *et* *al.*, 2007), which can have a synergistic effect on the factors that interact directly with recruitment variability.

In the present work, the NAO significantly influenced the catches of juveniles with a time lag of two months, with the negative phase being related to higher juvenile densities. Considering the influence of the NAO on the environmental conditions described previously, the spawning and recruitment processes on the coastal area may have been influenced up to some degree. A similar pattern has been observed in the Thames estuary (United Kingdon) by Attrill and Power (2002), in which the NAO significantly influenced the abundance of *C. crangon* over a 16-year period.

Coastal wind speed and direction, particularly the north-south component, was also significant in explaining the abundance trends of juveniles and the whole population, measured in the corresponding month. The negative values of the north-south wind (which component correspond to northerly winds), the dominant winds in the Portuguese coast, are usually responsible for coastal upwelling, inducing also Ekman transport of the surface water away from the coast (Huthnance, 1995; Smyth *et al*., 2001; Mason *et al.,* 2005). In this case, the wind blows parallel to the coast, which tends to drive the ocean surface currents to the right of the wind direction, pushing surface waters offshore. As surface waters are pushed offshore, water is drawn from below to replace them. The upward movement of this deep, colder water is called upwelling, creating a potential barrier to the migration of shrimps into estuarine waters. In agreement, in the present work, juvenile and the whole population higher densities were observed when wind values were close to zero, reducing the possibility of turbulence and advection that can constrain their transport to the estuary.

The transport processes of *C. crangon* larvae towards estuaries are still uncertain. On one hand, some authors stated that larvae are transported passively, being swirled up in the water column by increasing tidal because of wind induced currents and sinking down at low current velocities (Rijnsdorp *et al*., 1985; Bergman *et al*., 1989). On the other hand, it has been pointed out that larvae are also able to control somehow their transport selectively, by swimming up from the seabed during flood tides and remaining on the seabed during ebb tides (*i.e.* selective tidal transport) as observed in flatfish species (Rijnsdorp *et al*., 1985; Jager, 1999). Nevertheless, the process of estuarine colonization by shrimp larvae seems to be influenced by the prevailing weather conditions such as wind, currents and tides.

The abundance trends of juveniles were also influenced by river runoff. River runoff was highly variable during the surveyed period, resulting in a series of drought and non-droughts scenarios. They had responded positively to higher river runoff, which on one hand might be related with the extension of river plumes in the coastal areas, which is as observed for several fish species (e.g. Vinagre *et al*., 2007; Martinho *et al*., 2009). On the other hand, juveniles are more tolerant to lower salinity levels. This means that when the runoff is high the salinity drops, making the adult population migrate therefore leaving more space, food availability and reducing the cannibalism (Marchand, 1981), increasing the density of juveniles.

Overall, climate patterns seemed to influence, up to some degree, the abundance trends of *C. crangon* over the study period. Since estuaries act as a nursery area for this species, as well as for several other invertebrates and fish, they have a potentially critical role in dampening climate-induced stock fluctuations, as observed by Attrill & Power (2002). Thus, monitoring and protection measures should be directed towards estuaries, in order to preserve and enhance their capability of replenishing the coastal (and estuarine) stocks of commercially exploited estuarine-dependent species.

Chapter 5

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